

III. Electromagnetic uniformity: finite RF wavelength in large area, VHF reactors: **standing waves, and telegraph effect**

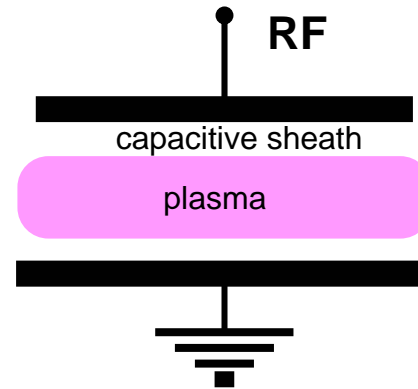
- IV. Uniformity in time: minimize transients, rapid equilibration to steady-state process parameters
 - Direct pumping of a plasma reactor.
- V. So where is the problem? - Causes of non-uniformity. Some recommendations.

Motivations for Very High Frequency (VHF: 30 - 300 MHz)

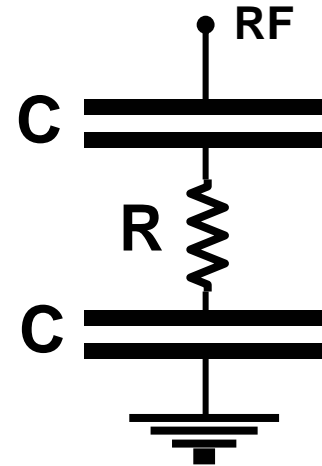
adapted from Jacques Schmitt Orleans ISPC XV 2001.

Larger power in for:

- less sheath voltage
- less ion bombardment
- better film quality
- higher deposition rate
- reduced dust build up



over-simplified
equivalent
circuit
for plasma

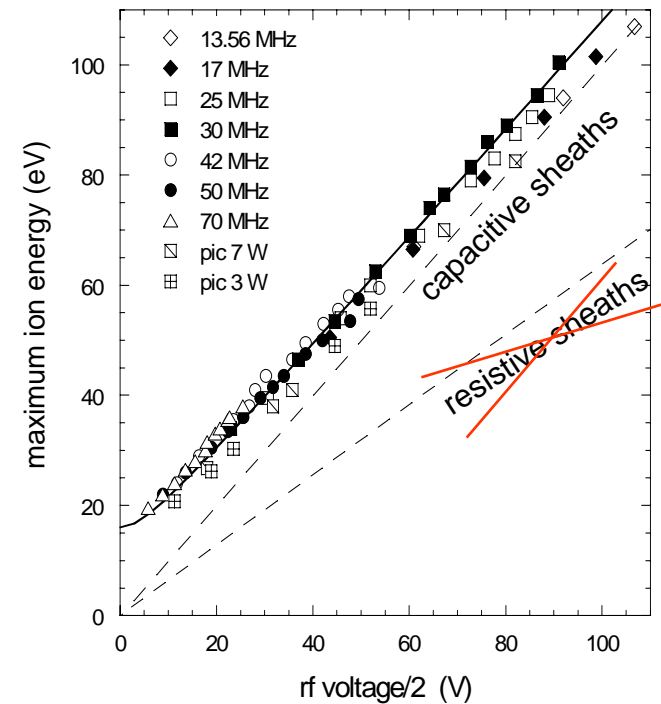


"For a given RF power in the plasma, require a given RF current i_{RF} in the resistive plasma. Sheath capacitances C dominates the total impedance.

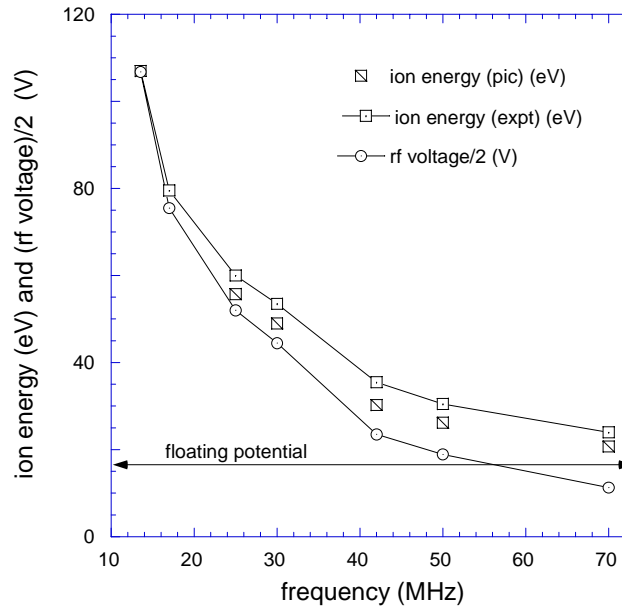
For the current i_{RF} , the RF Voltage across a capacitive sheath is $V_{\text{RF}} = \frac{i_{\text{RF}}}{2\pi f_{\text{RF}} C}$.

Therefore higher frequency has lower RF sheath voltage for given RF power"

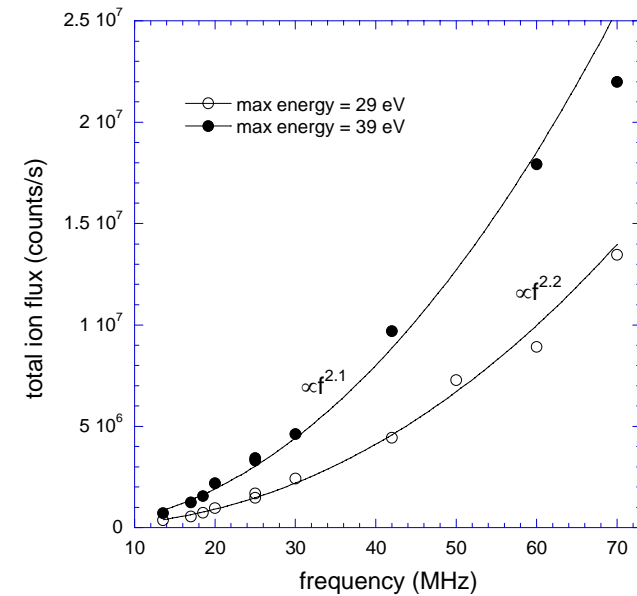
Motivation for VHF - some experimental measurements



ion energy \sim half RF voltage amplitude for a symmetric plasma reactor



For constant RF power:
RF voltage decreases with frequency, therefore the ion energy decreases (down to floating potential)



For constant ion energy:
ion flux increases with frequency

W. Schwarzenbach, A. A. Howling, M. Fivaz, S. Brunner, Ch. Hollenstein,
J. Vac. Sci. Technol. A **14** 132 (1996)

Very large plasma capacitor

1980 
20 cm

Reactor diagonal: 400 cm

2005 

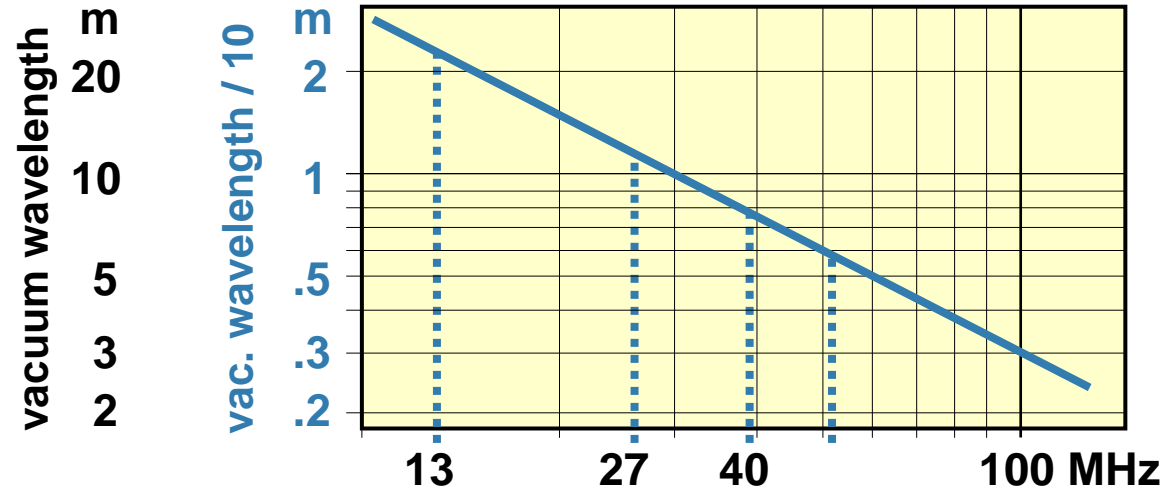
THE “NO-LONGER” LIST:

- ***RF wave length \gg reactor size? No***

**First electromagnetic source of non-uniformity:
Very High Frequency and the standing-wave problem**

standing wave effect

need reactor dimension less than
1/10 of vacuum wavelength
(factor 4 for node-antinode, and
factor ~2.5 for worsening effect)



For 1 m diagonal,

- standing wave barely observable at 13 MHz
- contributing to profile non-uniformity at 27 MHz
- strong non-uniformity at 70 MHz

For 2 m diagonal,

- even 13 MHz is a problem

adapted from Jacques Schmitt Orleans ISPC XV 2001.

RF coupling and RF voltage homogeneity

Examples

13.56 MHz

RF coupling point

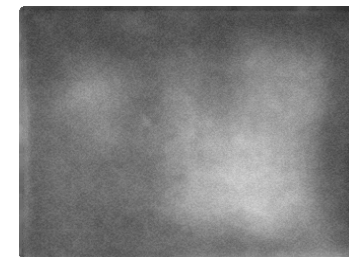
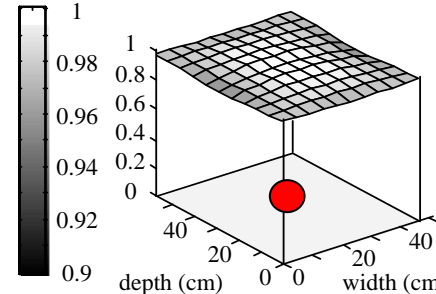
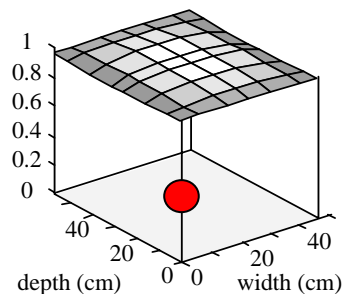
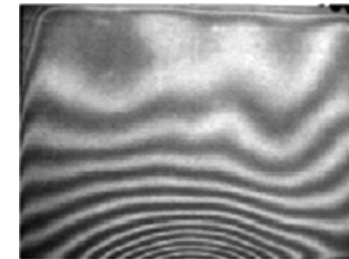
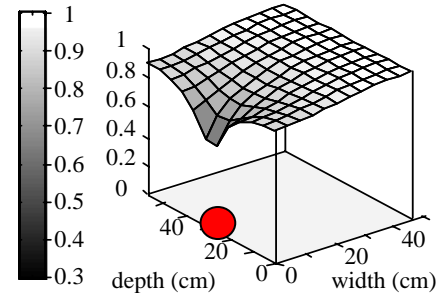
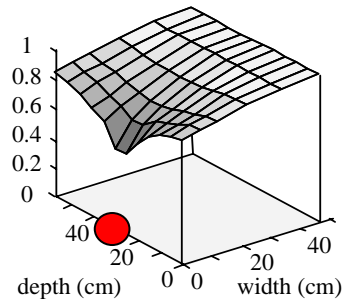
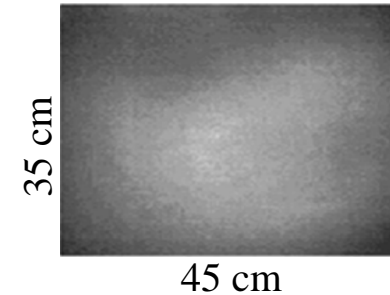
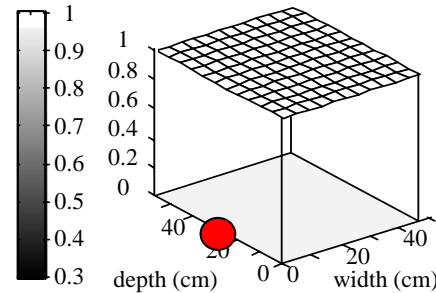
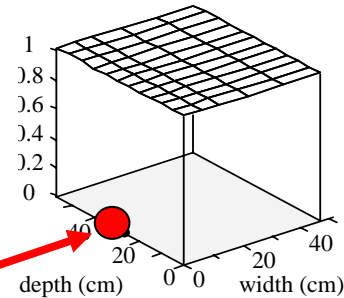
edge 70 MHz

centre 70 MHz

Experiment

Calculation

Film thickness
interferogram



High frequency vacuum capacitor

from Feynman lectures :

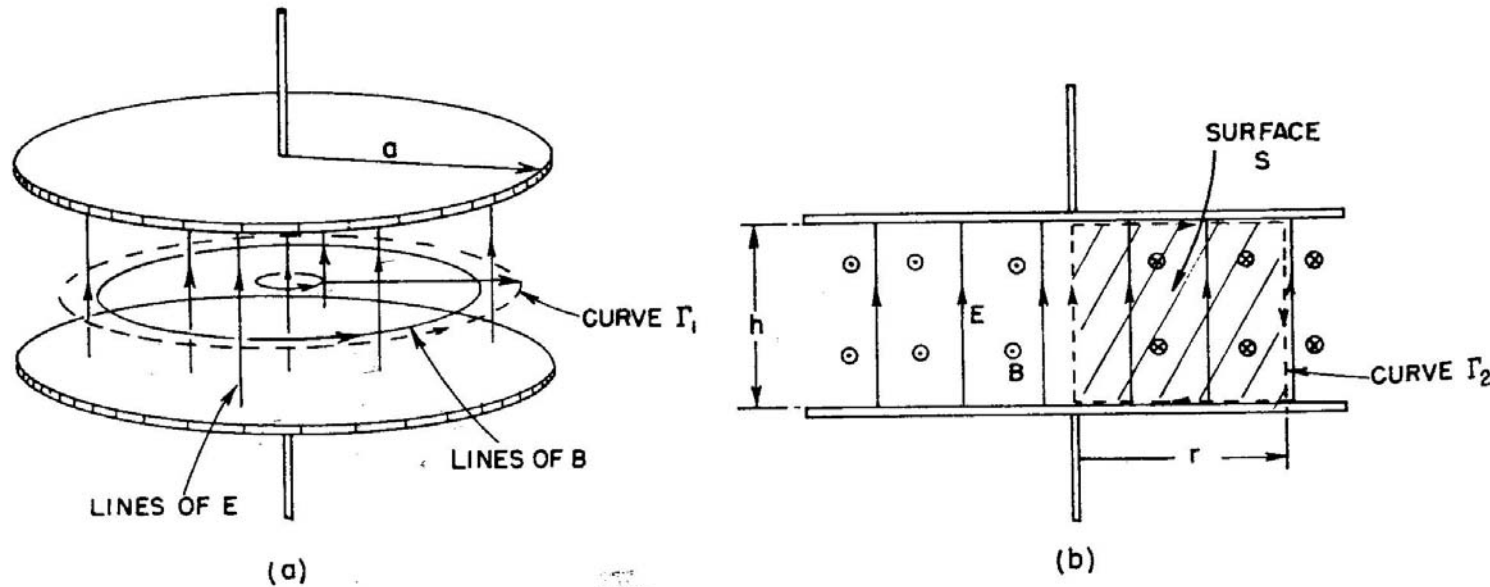


Fig. 23-4. The electric and magnetic fields between the plates of a capacitor.

self-consistent solution of oscillating E and B fields
an *electromagnetic* solution is necessary; *no longer electrostatic!*



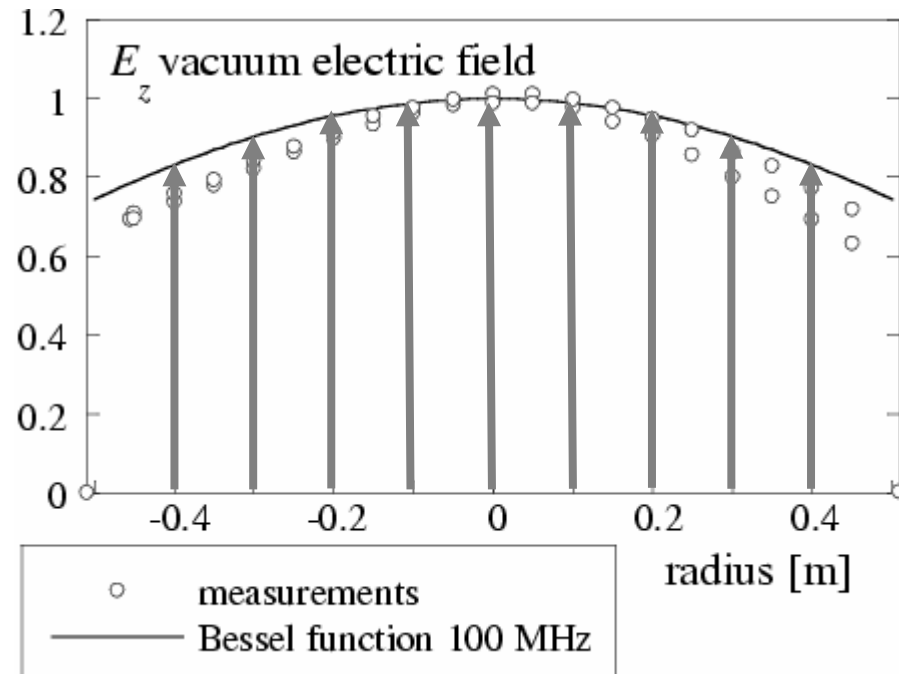
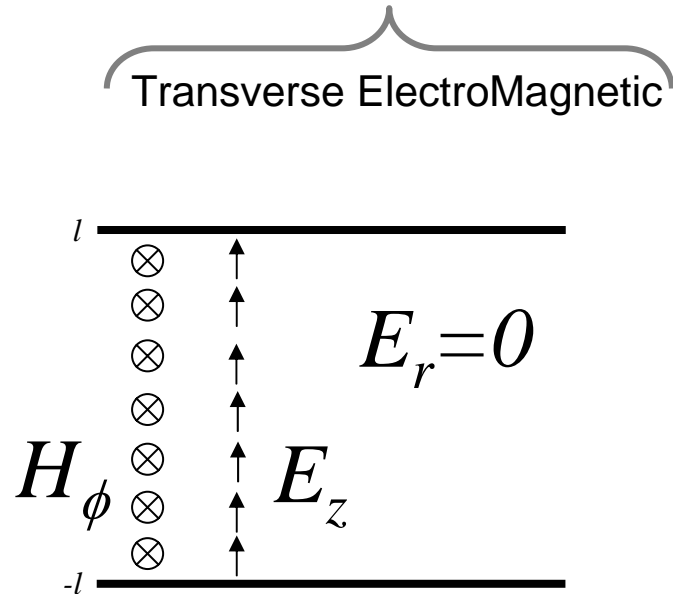
plates are not equipotential: **Bessel function distribution**

Axisymmetric H_ϕ in a cylindrical reactor

wave equation $(\nabla^2 \underline{H} + k_0^2 \underline{H})_\phi = 0$

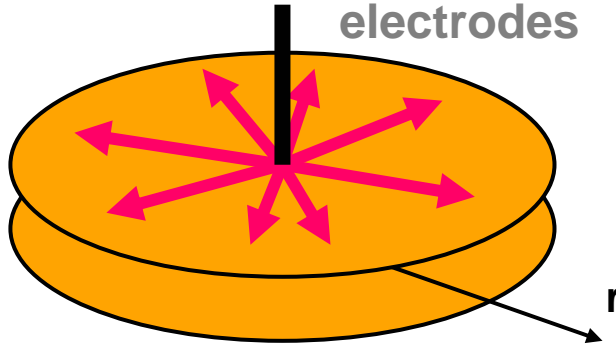
field equation $\frac{1}{\epsilon} \left[\frac{\partial^2 H_\phi}{\partial r^2} + \frac{1}{r} \frac{\partial H_\phi}{\partial r} - \frac{1}{r^2} H_\phi \right] + \frac{\partial}{\partial z} \left[\frac{1}{\epsilon} \frac{\partial H_\phi}{\partial z} \right] + k_0^2 H_\phi = 0$

vacuum TEM mode Bessel function $J(k_0 r)$

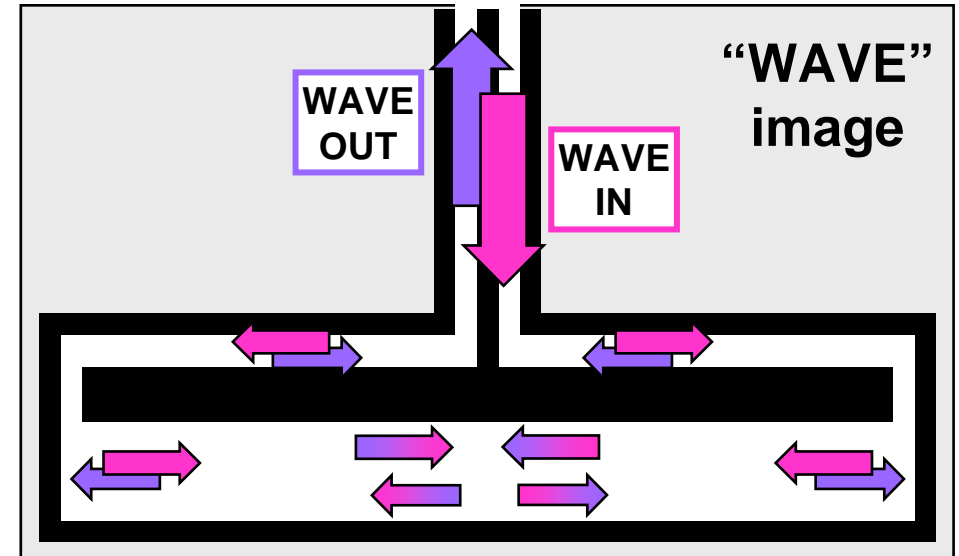


The capacitor in a vacuum chamber:

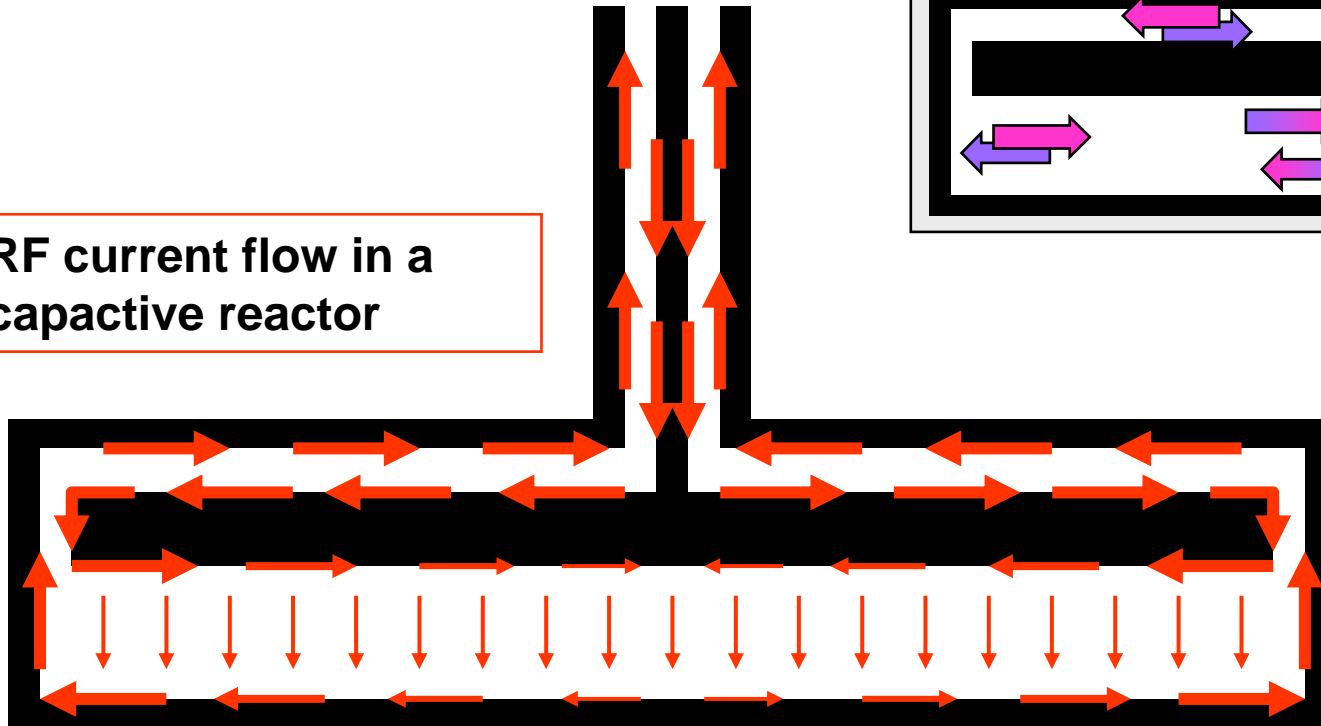
small skin depth in metal
electrodes



The hand-waving description



RF current flow in a
capactive reactor



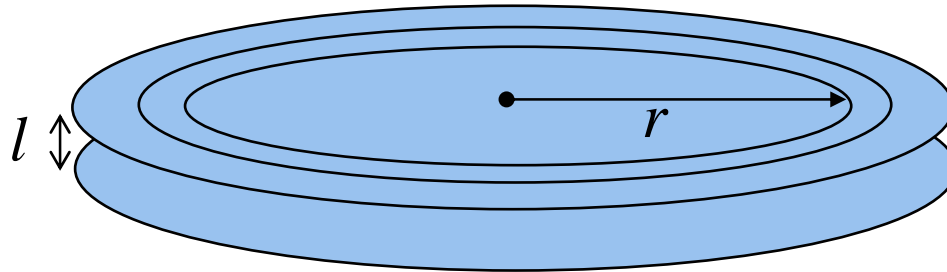
RF power
propagates
inwards from
the edges

courtesy of Jacques Schmitt



CYLINDRICAL TRANSMISSION LINE APPROACH (6 optional slides)

Admittance of cylindrical parallel plates, gap l



Capacitance of parallel plates, $C = \frac{\epsilon_0 A}{l}$

Elemental cylindrical capacitance, $dC = \frac{\epsilon_0 2\pi r dr}{l}$

Capacitance per unit length in cylinder along $r = \frac{\epsilon_0 2\pi r}{l}$

Capacitive impedance $= \frac{1}{j\omega C}$, admittance $= j\omega C$.

Admittance per unit length (along r) of cyl. parallel plates, $Y = j\omega \frac{\epsilon_0 2\pi r}{l}$

Effective permittivity of plasma-&-sheaths



Plasma short-circuits the transverse electric field:

$$\text{Combined capacitance of sheaths} = \frac{\epsilon_0 A}{2s},$$

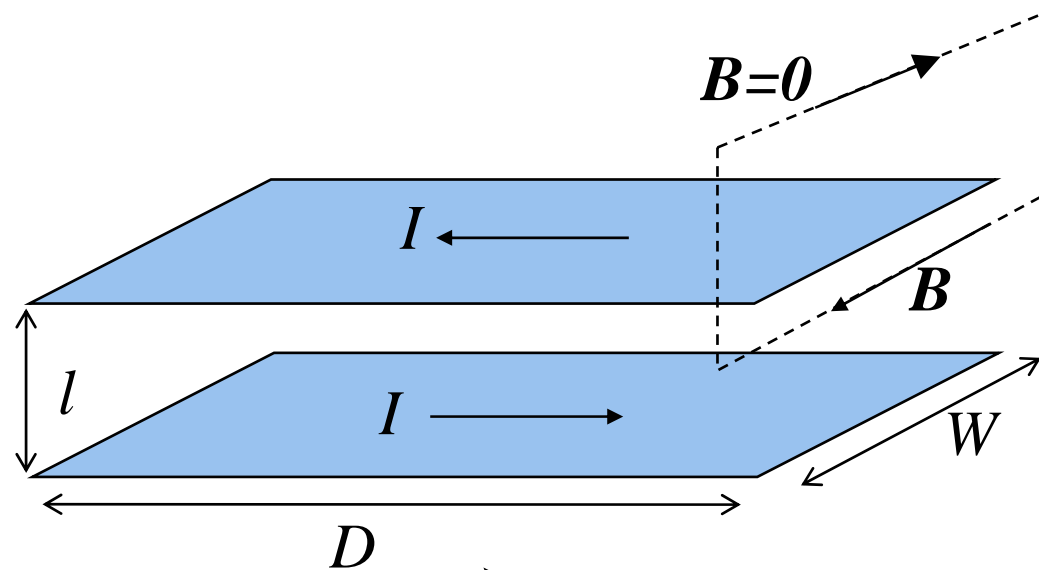
$$\text{Effective capacitance of the gap} = \frac{\epsilon_0 \epsilon_{\text{eff}} A}{l},$$

$$\therefore \text{Effective permittivity of the gap, } \epsilon_{\text{eff}} = \frac{l}{2s}.$$

Effective admittance per unit length (along r) of plasma-&-sheaths

$$\text{in cylindrical parallel plates, } Y = j\omega\epsilon_0\epsilon_{\text{eff}} \frac{2\pi r}{l}.$$

Series impedance of parallel plates



Ampere's law (uniform \vec{B} between plates):

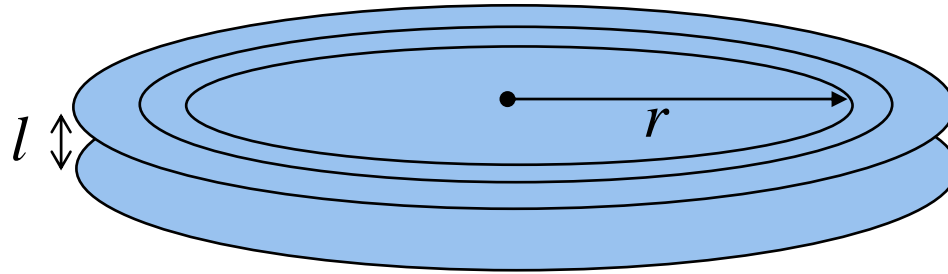
$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I,$$

$B = \mu_0 I / W$, unaffected by plasma ($\mu_r = 1$),

$$\text{Flux } \Phi = B \cdot lD = \mu_0 I \cdot lD / W$$

$$\text{Parallel plate inductance, } L = \Phi / I = \mu_0 lD / W$$

Series impedance of cylindrical parallel plates, gap l

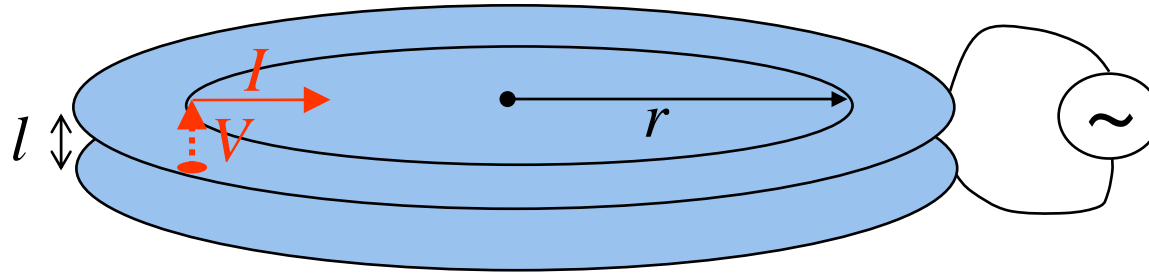


Inductance of cylindrical element, $dL = \frac{\mu_0 l dr}{2\pi r}$,

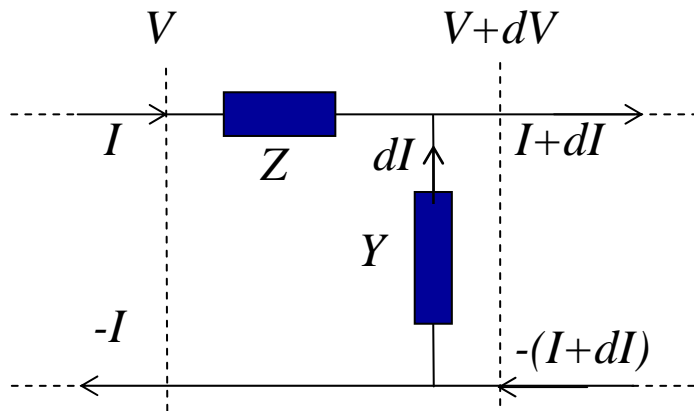
Impedance of cylindrical element $= j\omega \frac{\mu_0 l dr}{2\pi r}$.

Series impedance in cylinder per unit length along r , is $Z = j\omega\mu_0 \frac{l}{2\pi r}$.

Consider a *general* cylindrical transmission line



Uniform voltage and current around the circumference, open circuit on axis, series impedance Z , and parallel admittance Y , per unit length along r .



Kirchoff's laws: $\frac{dV}{dr} = -IZ$, $\frac{dI}{dr} = -YV$.

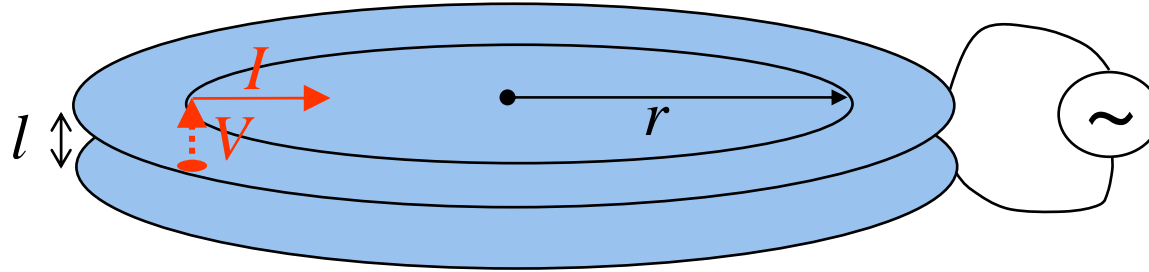
Substitute for I (or for V):

$$\frac{d^2V}{dr^2} = \left(\frac{1}{Z} \frac{dZ}{dr} \right) \frac{dV}{dr} + YZV, \text{ which is the}$$

general voltage wave equation.

Consider a *parallel-plate* cylindrical transmission line

gap is constant,
V is variable.



Use the parallel-plate expressions: $Z = j\omega\mu_0 \frac{l}{2\pi r}$, $Y = j\omega\epsilon_0\epsilon_{\text{eff}} \frac{2\pi r}{l}$

$\therefore \left(\frac{1}{Z} \frac{dZ}{dr} \right) = -\frac{1}{r}$ and the general cylindrical transmission line equation is:

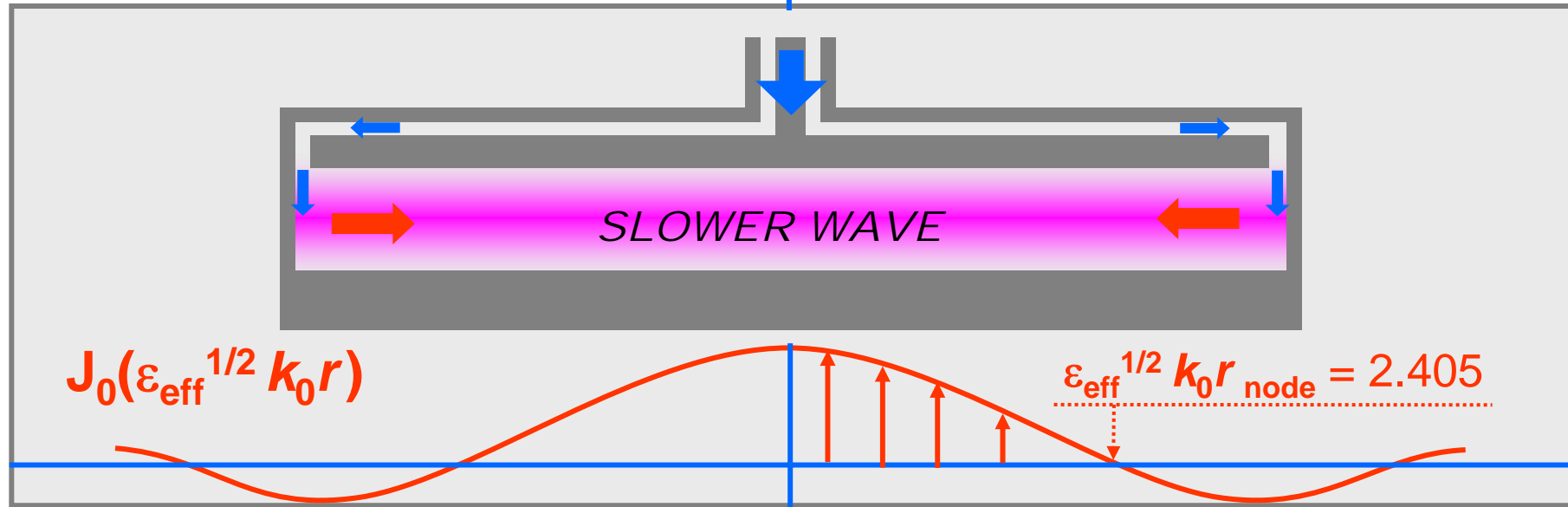
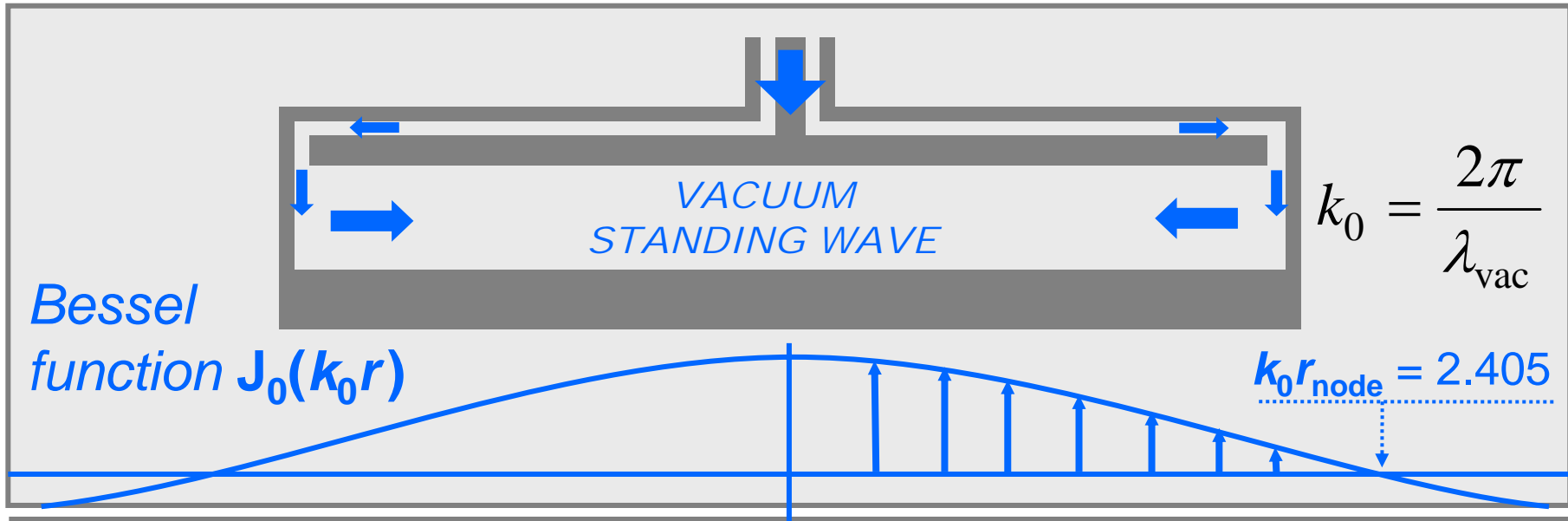
$$\frac{d^2V}{dr^2} + \frac{1}{r} \frac{dV}{dr} + k^2V = 0, \text{ the voltage wave equation in cylindrical geometry,}$$

Bessel function solution $J_0(kr)$, where $k^2 = -YZ = \omega^2\mu_0\epsilon_0\epsilon_{\text{eff}} = k_0^2\epsilon_{\text{eff}}$;

$$k_0 = \frac{2\pi}{\lambda_{\text{vac}}}, \quad k = k_0\sqrt{\epsilon_{\text{eff}}}, \text{ and the wave phase velocity} = \frac{1}{\sqrt{\mu_0\epsilon_0\epsilon_{\text{eff}}}} = \frac{c}{\sqrt{\epsilon_{\text{eff}}}}.$$

(sheath width s , $\therefore \epsilon_{\text{eff}}$, assumed independent of V)

Effect of plasma on vacuum capacitor

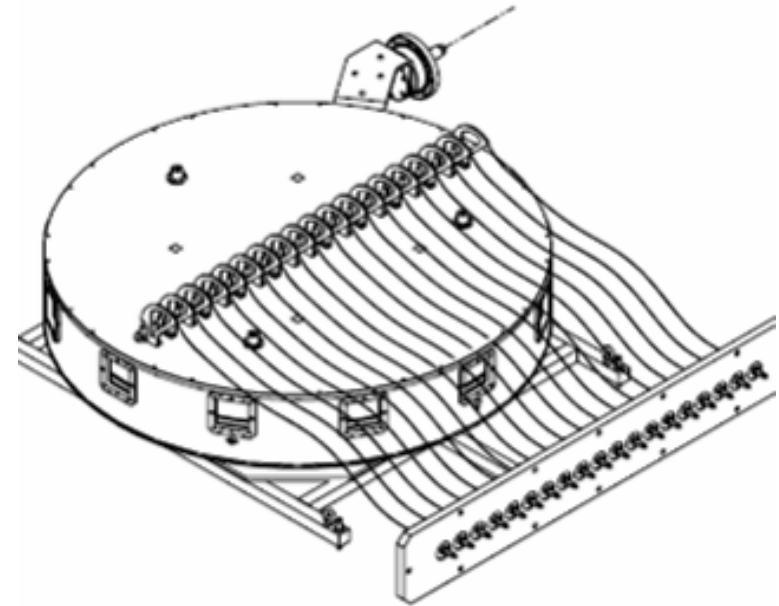
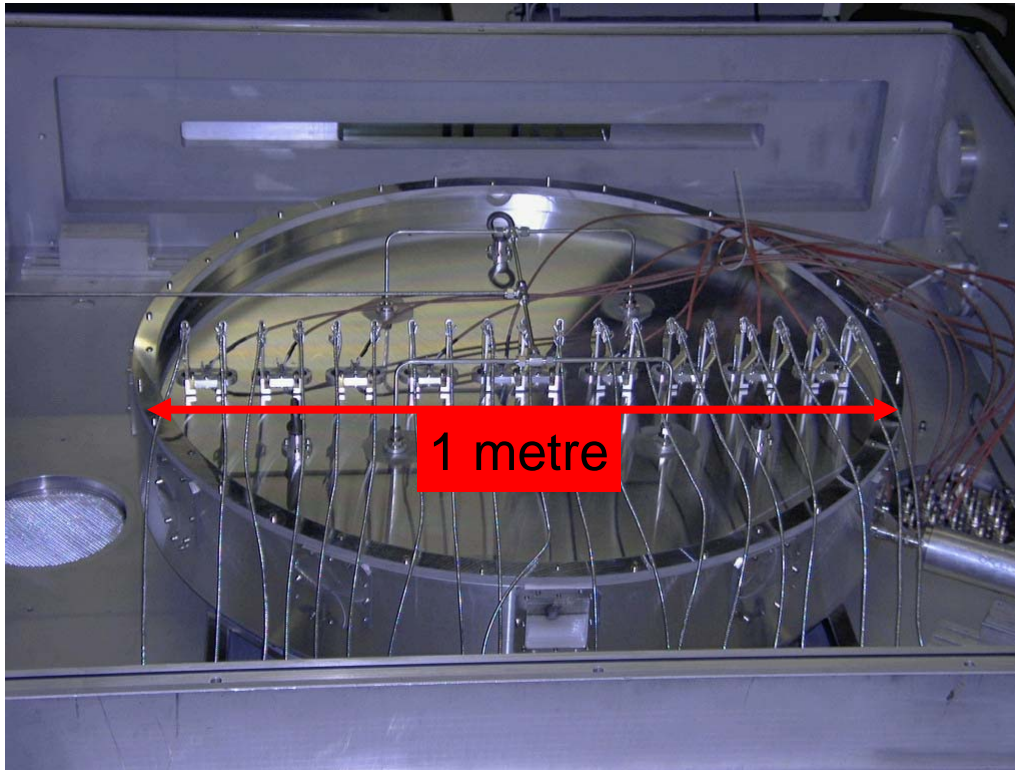


ϵ_{eff} "equivalent dielectric" acts as a worsening factor for uniformity

courtesy of Jacques Schmitt

Cylindrical reactor experiment

optical emission & surface electrostatic probes

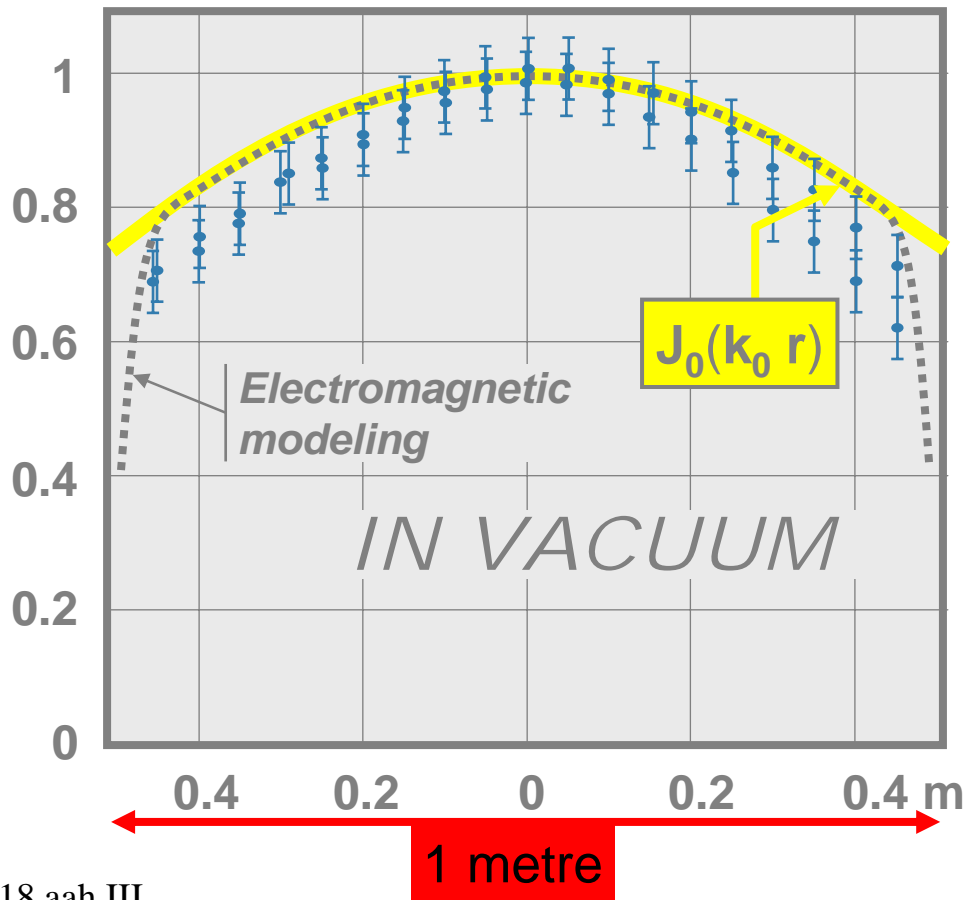


H. Schmidt, L. Sansonnens, A. A. Howling, and Ch. Hollenstein, *J. Appl. Phys.* **95**, 4559 (2004)

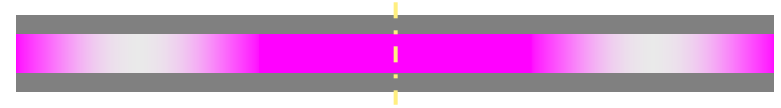
Standing wave effects

EXPERIMENTS AT 100 MHz

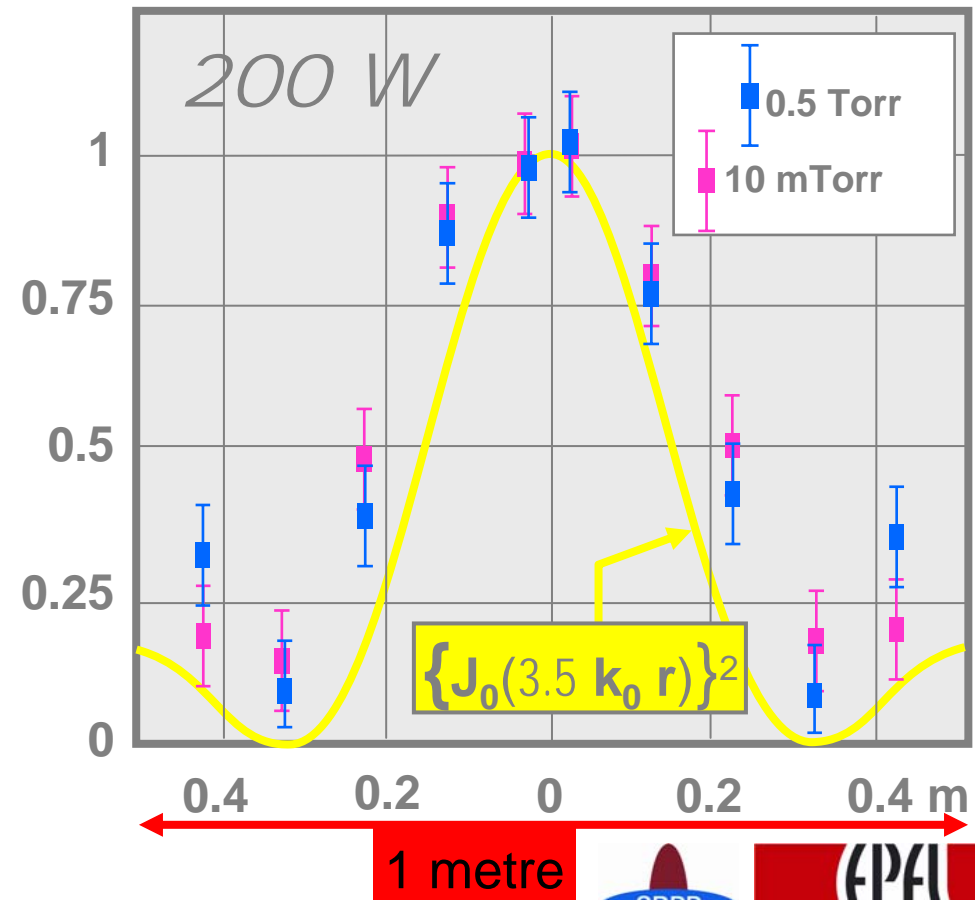
E-field relative profile at 100 MHz
(bench test with scanning probe)



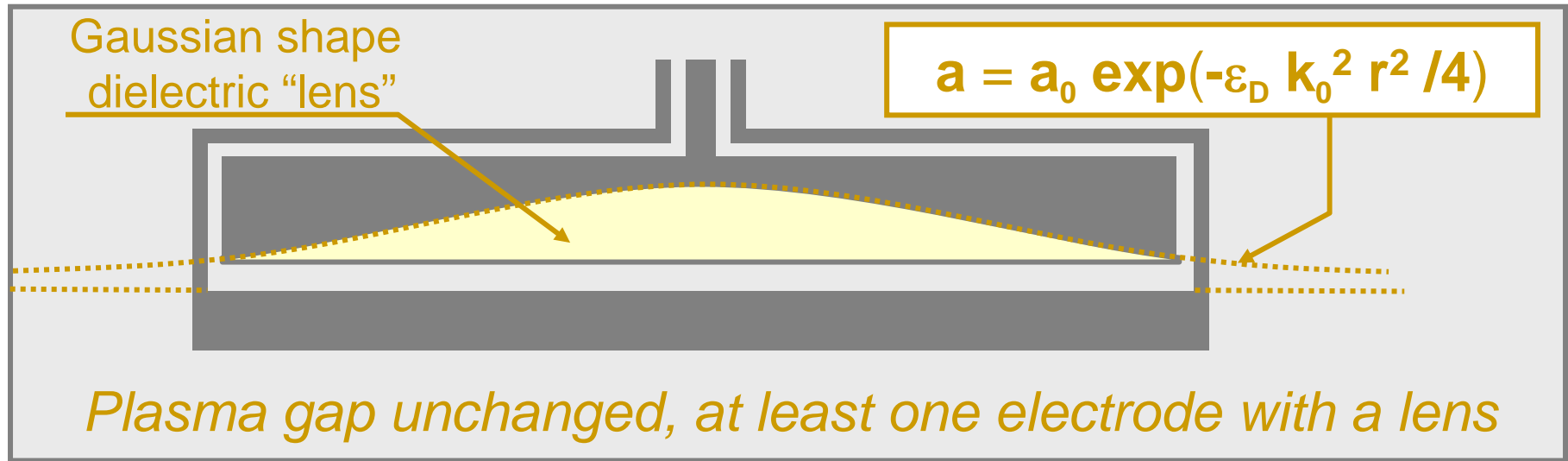
With plasma, the first node moves inside:
dark ring at $r = 0.3$ m!



probe array ion saturation currents
(normalized to the central values)

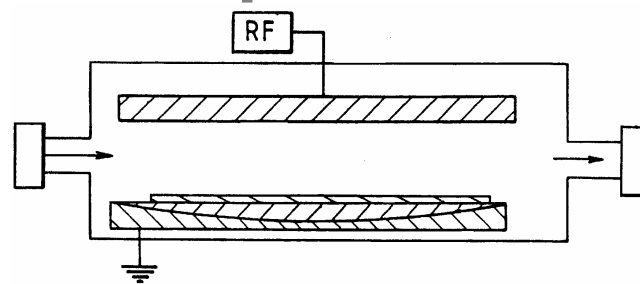


A compensation solution



- Solution of Maxwell's equations
- Constant vertical E-field across the diameter
- Still valid in presence of a plasma

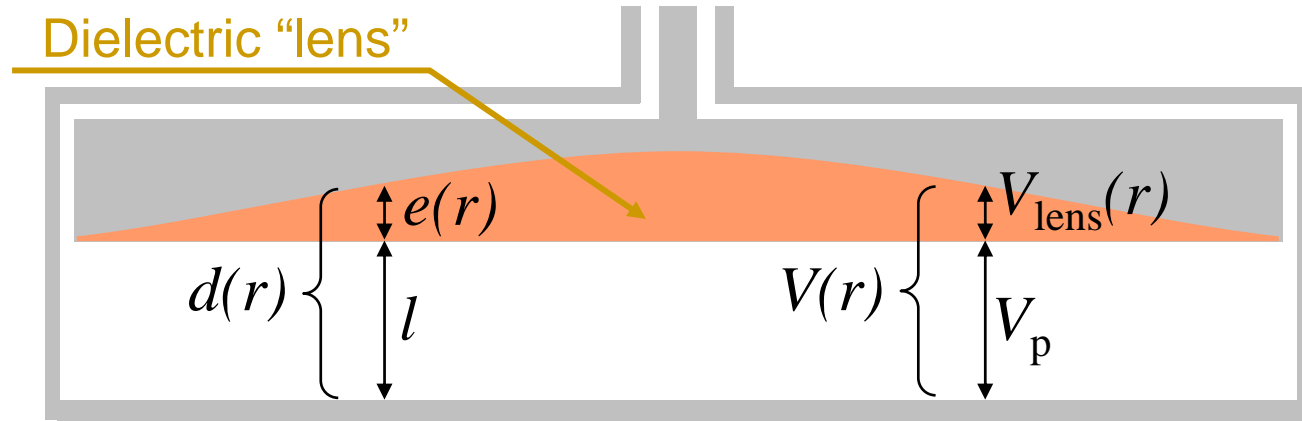
Fig.2 of Patent US.6228438
(Unaxis) **1999**



World's Simplest Lens Solution (4 optional slides)

adapted from P. Chabert *et al*, *Phys. Pl.* **11**, 4081 (2004)

gap is variable,
 V_p is constant.



We keep a constant plasma gap, l ,
but add a variable thickness lens $e(r)$.

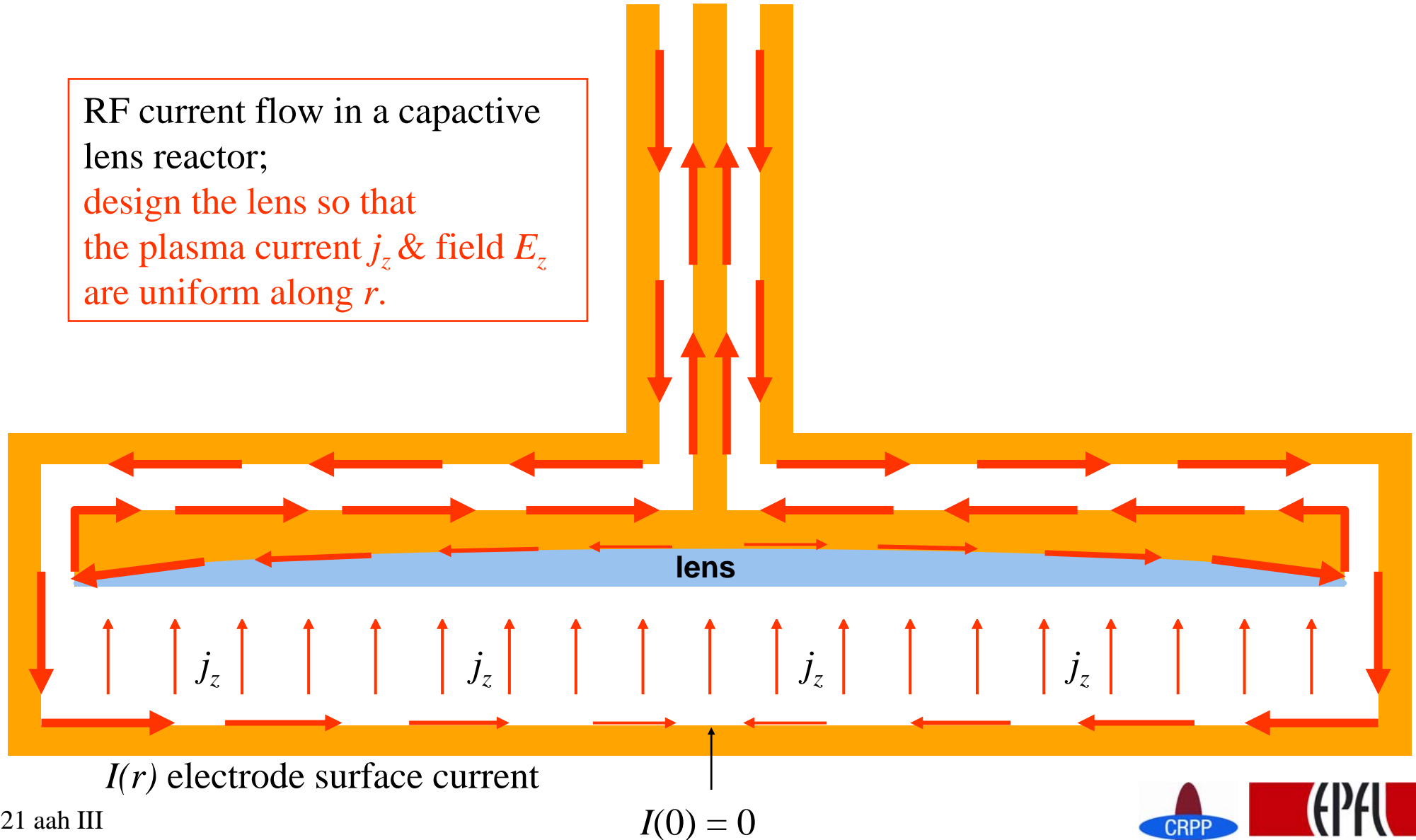
Total electrode gap is now $d(r) = l + e(r)$.

The plasma voltage is V_p , which we *define* constant,
the voltage across the lens thickness is $V_{\text{lens}}(r)$.

The total electrode voltage is $V(r) = V_p + V_{\text{lens}}(r)$.

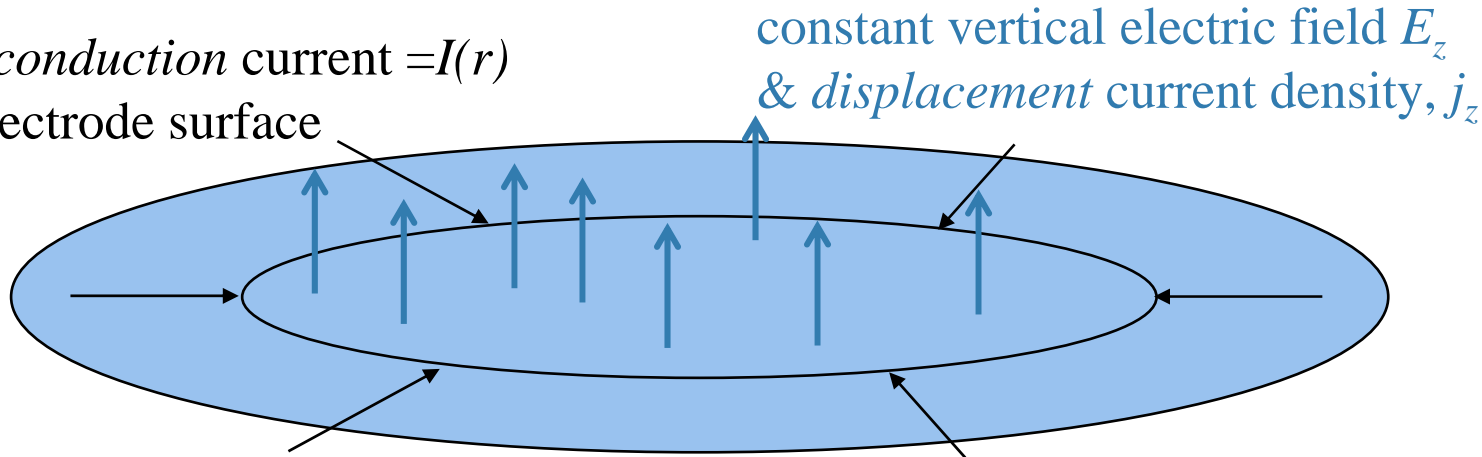
World's Simplest Lens Solution; introduction

RF current flow in a capacitive lens reactor;
design the lens so that
the plasma current j_z & field E_z
are uniform along r .



World's Simplest Lens Solution.

total radial *conduction* current $= I(r)$
along the electrode surface



1) We require a constant vertical electric field in gap, $E_z = \frac{V_p}{l} = \text{const.}$

2) \therefore require constant vertical current density $j_z = \frac{j\omega\epsilon_0\epsilon_{\text{eff}}V_p}{l} = \boxed{\frac{j\omega\epsilon_0\epsilon_r V_{\text{lens}}(r)}{e(r)}}$.

3) The radial current in electrodes, $I(r) = -j_z \pi r^2$
(all the current entering radius r radially, must leave vertically,
because $I(0) = 0$, and $j_z = \text{constant over all } r$.)

World's Simplest Lens Solution.

4) To calculate $V(r)$, use Ohm's law radially: $dV(r) = -I(r)Z(r)dr$,

where $Z(r) = j\omega\mu_0 \frac{d(r)}{2\pi r}$ is the series impedance of the gap, per unit radius.

5) Substitute: $\frac{dV(r)}{dr} = j_z \pi r^2 Z = \frac{j\omega\epsilon_0\epsilon_r V_{\text{lens}}(r)}{e(r)} \pi r^2 \cdot j\omega\mu_0 \frac{d(r)}{2\pi r}$,

$\therefore \frac{dV_{\text{lens}}(r)}{dr} = -k_0^2 \epsilon_r V_{\text{lens}}(r) \frac{d(r)}{e(r)} \frac{r}{2}$, since $V(r) = V_{\text{lens}}(r) + V_p$.

6) Substitute for $V_{\text{lens}}(r)$ using 2): $V_{\text{lens}}(r) = \frac{\epsilon_{\text{eff}}}{\epsilon_r} \frac{V_p}{l} e(r)$ so that

$e'(r) = -k_0^2 \epsilon_r d(r) \frac{r}{2}$, and since $d(r) = e(r) + l$, $d'(r) = -k_0^2 \epsilon_r d(r) \frac{r}{2}$.

7) $\therefore d(r) = (l + e(0)) \exp\left(\frac{-k_0^2 \epsilon_r r^2}{4}\right)$, a Gaussian lens.

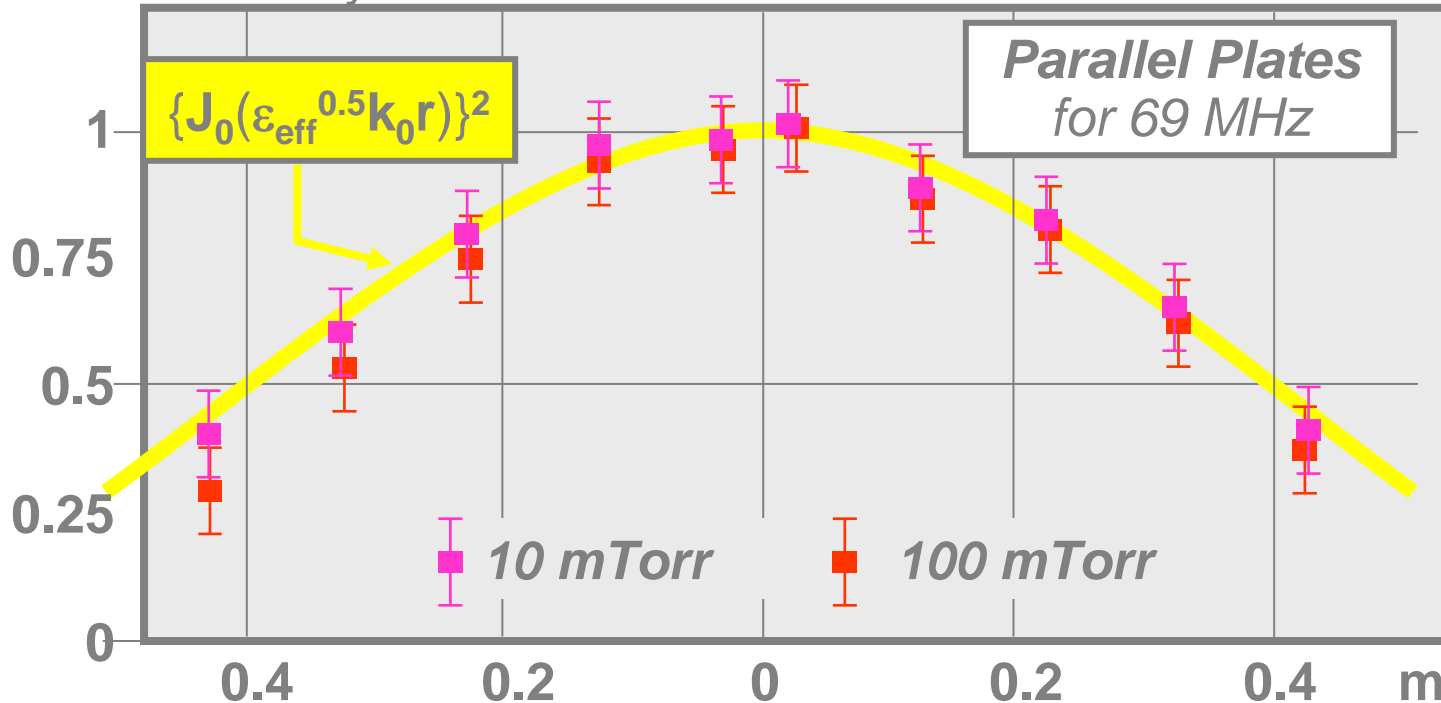
Shape depends on ϵ_r , not ϵ_{eff} , i.e. lens shape is independent of the plasma!

Also, $I(r)$ and $V_{\text{lens}}(r) \propto \epsilon_{\text{eff}}$ for given V_p .

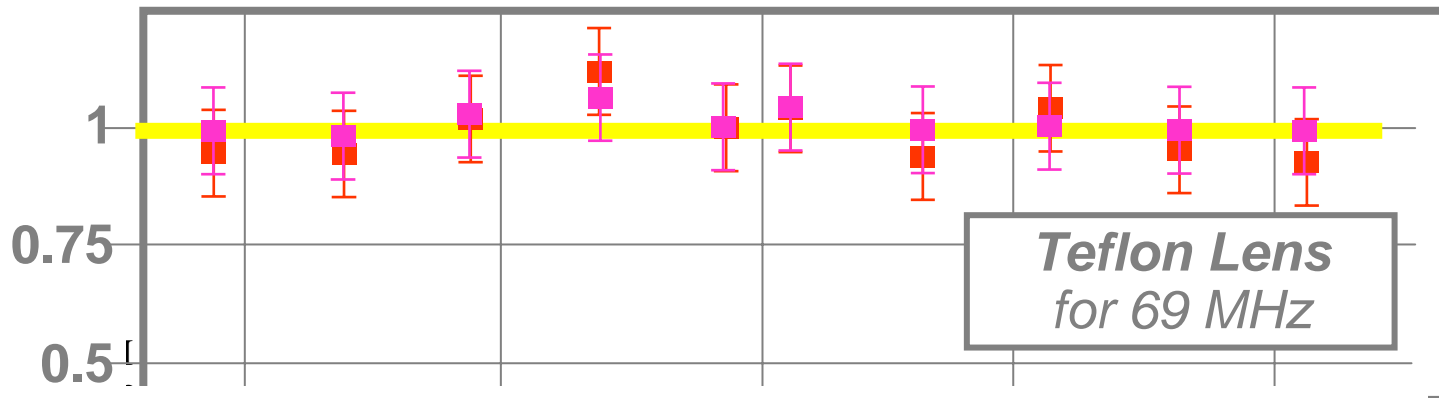
Experimental demonstration of a compensation lens



Probe array: ion current normalized to center




Very non uniform
a factor 3



Recovery
uniformity > 10%



Very large plasma capacitor

1980 
20 cm

2005 
Reactor diagonal: 400 cm

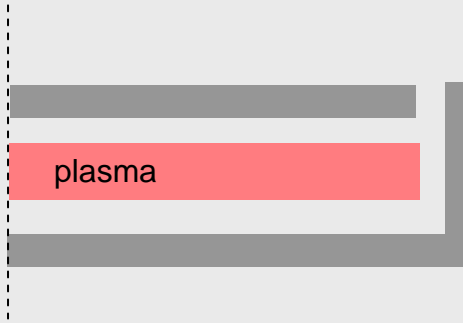
THE "NO-LONGER" LIST again

- ***RF plasma potential is constant? No***

**Second electromagnetic aspect :
Current flow over long, resistive plasma**

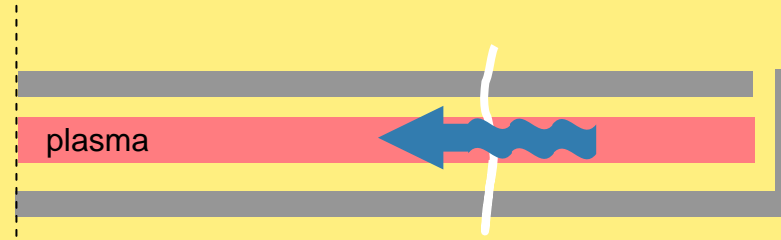
Edge perturbation due to a sidewall

Small area reactor



RF plasma potential averaged over the whole reactor - *unequal sheath voltages*

Large area reactor

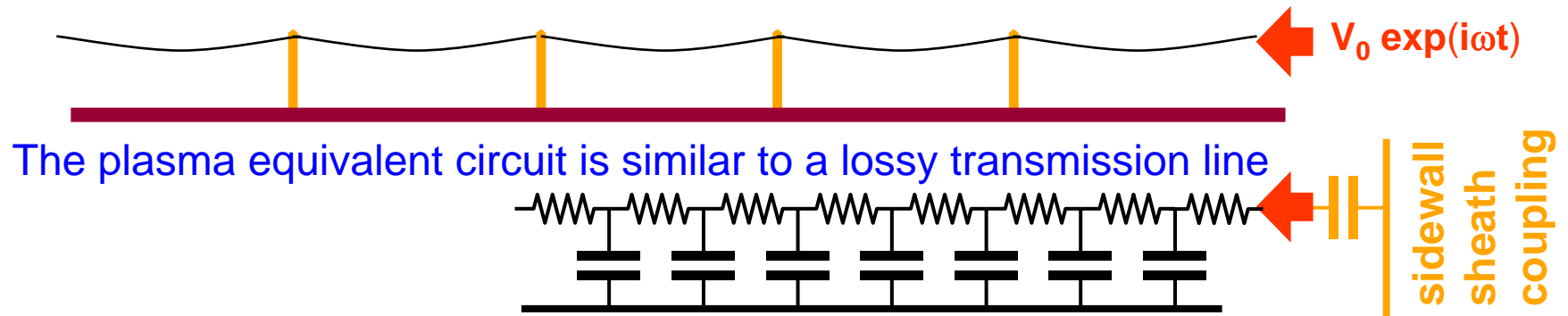


Symmetric centre – *equal sheath voltages*

Non-symmetric edge – *unequal sheath voltages*

RF plasma potential is not the same everywhere
– how does the perturbation propagate?

The telegraph equation



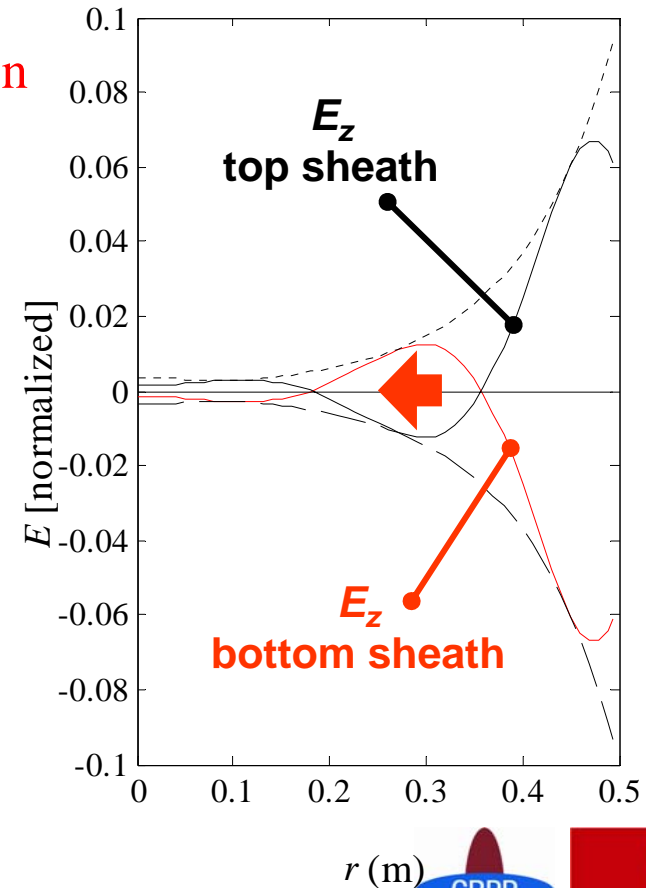
The plasma equivalent circuit is similar to a lossy transmission line

The propagation of the rf plasma potential perturbation \underline{V} is described by the telegraph equation

$$\nabla^2 \underline{V} = LC \frac{\partial^2 \underline{V}}{\partial z^2} + RC \frac{\partial \underline{V}}{\partial z}$$

for Bessel fetishists

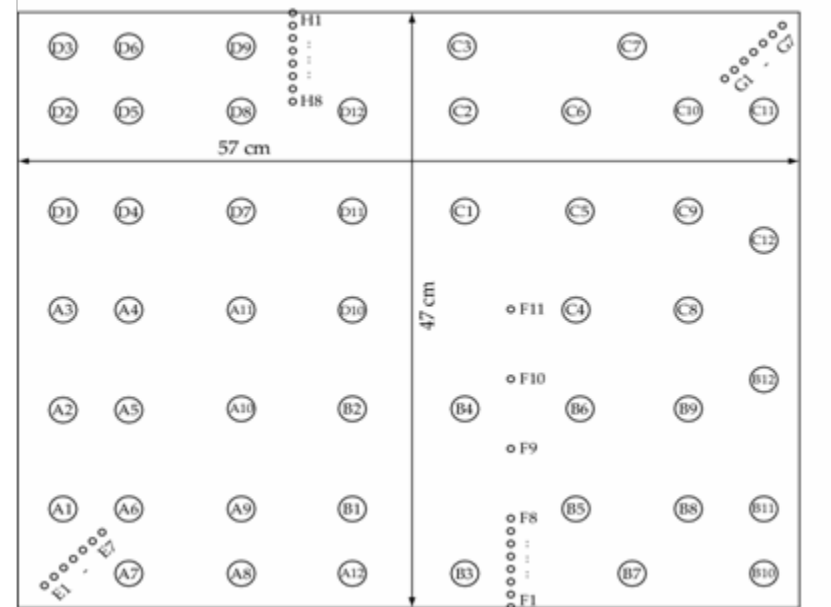
The first kind Bessel function for complex wavenumber k , $\text{Re}\{J_0(kr)\}$, is a damped standing wave which is almost equivalent to its inward-propagating damped traveling wave component $\text{Re}\{H_0^{(1)}(kr)\}$ (a Hankel function)



Telegraph effect: probe measurements

Rectangular reactor 47 x 57 cm²

81 surface probes for DC voltage and current measurements



Theory: A. A. Howling, L. Sansonnens, J. Ballutaud, Ch. Hollenstein, J. P. M. Schmitt, *J. Appl. Phys.* **96**, 5429 (2004)

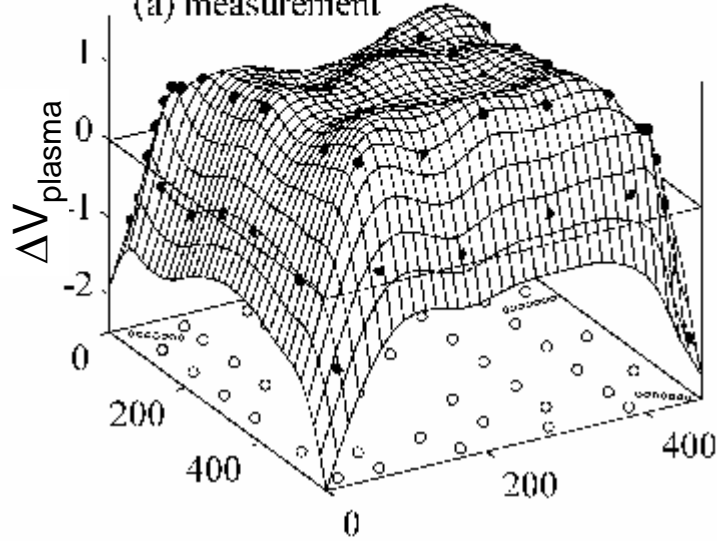
Experiment: A. A. Howling, L. Derendinger, L. Sansonnens, H. Schmidt, Ch. Hollenstein, E. Sakanaka, J. P. M. Schmitt, *J. Appl. Phys.* **97**, 123308 (2005)

Telegraph effect...

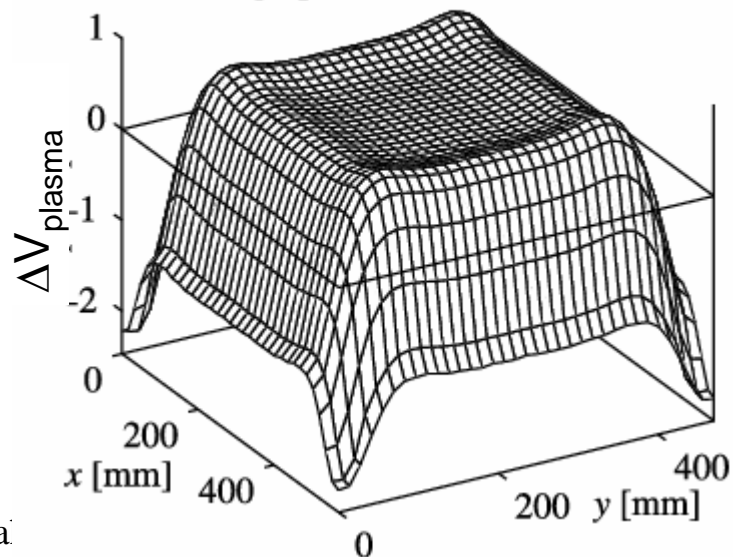
Case A

rf electrode
ground electrode

(a) measurement



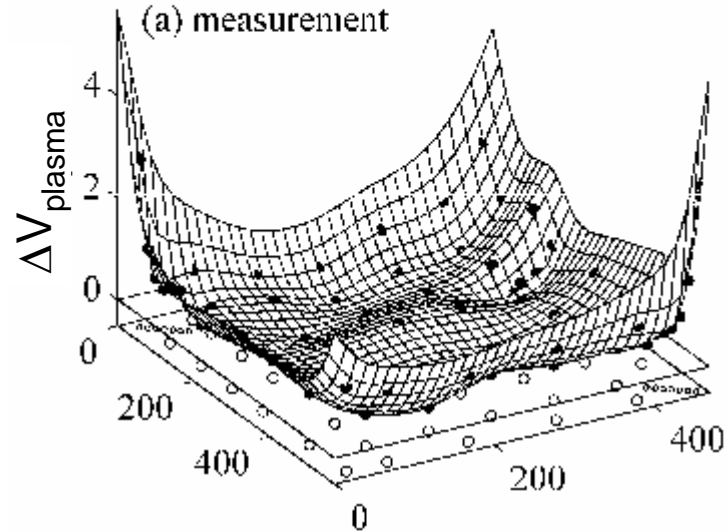
(b) telegraph solution



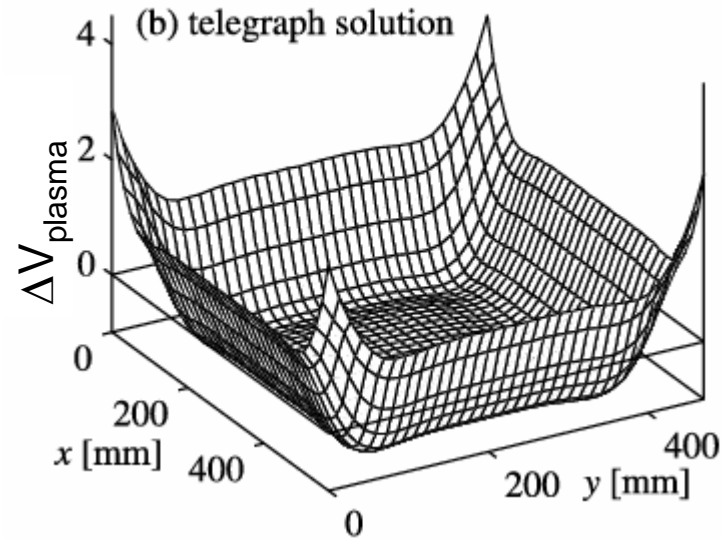
Case B - inverse asymmetry

rf electrode
ground electrode

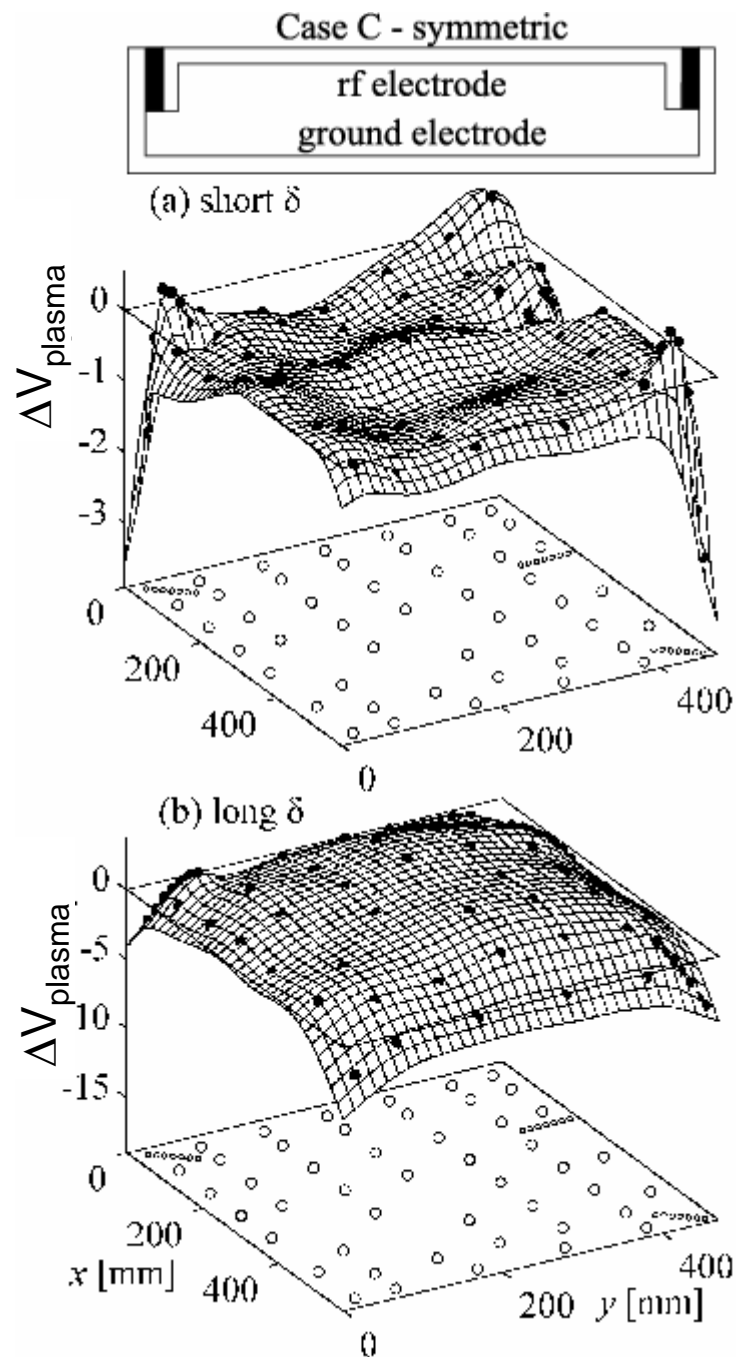
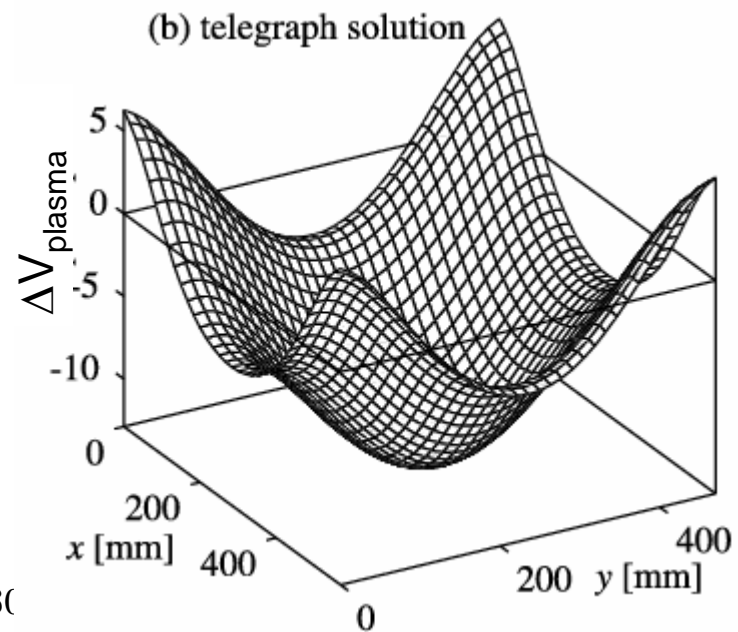
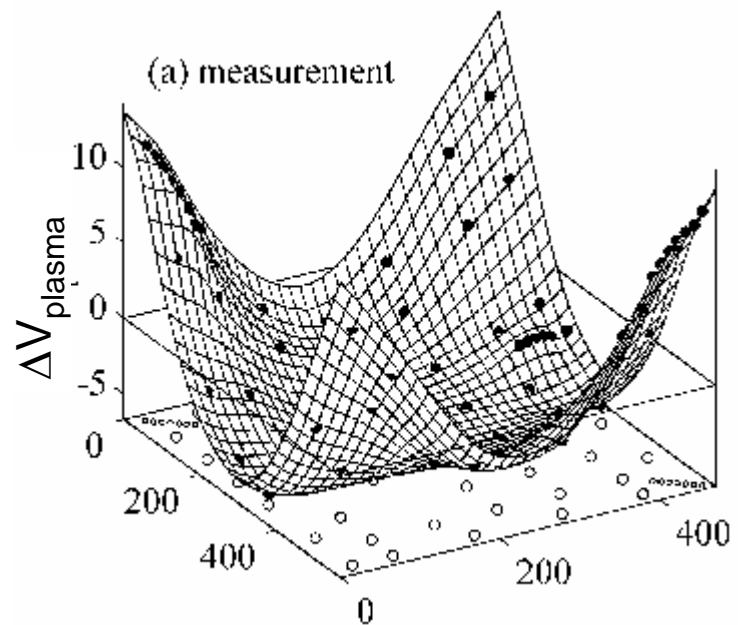
(a) measurement



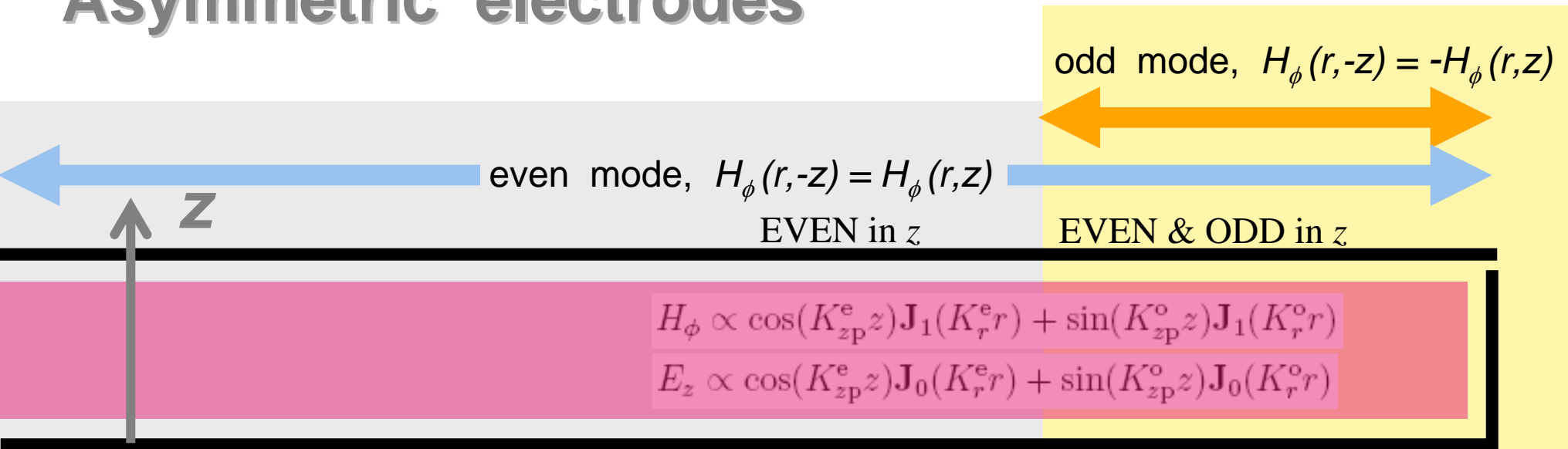
(b) telegraph solution



...demonstrated

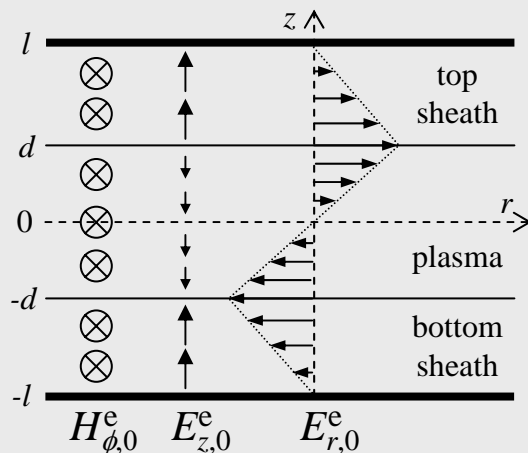


Asymmetric electrodes

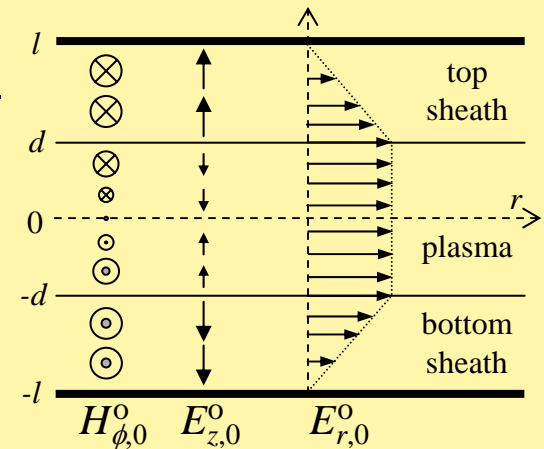


**the first even & odd quasi-TEM modes give the complete solution
(higher modes are evanescent)**

quasi-TEM
first even mode

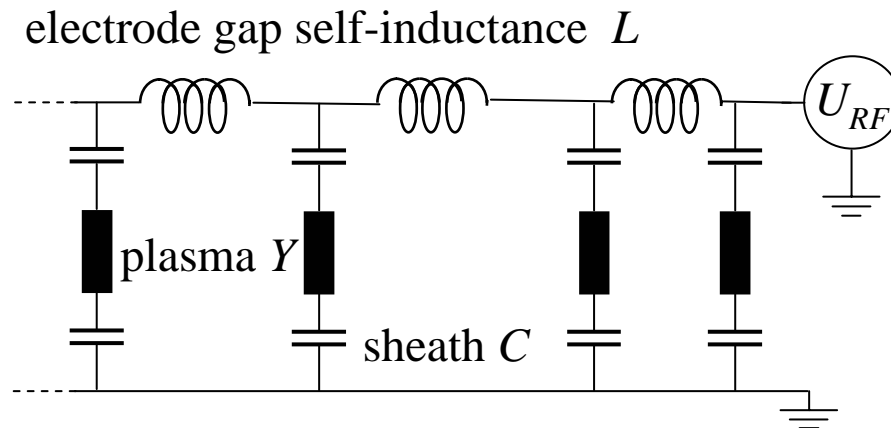


quasi-TEM
first
odd
mode

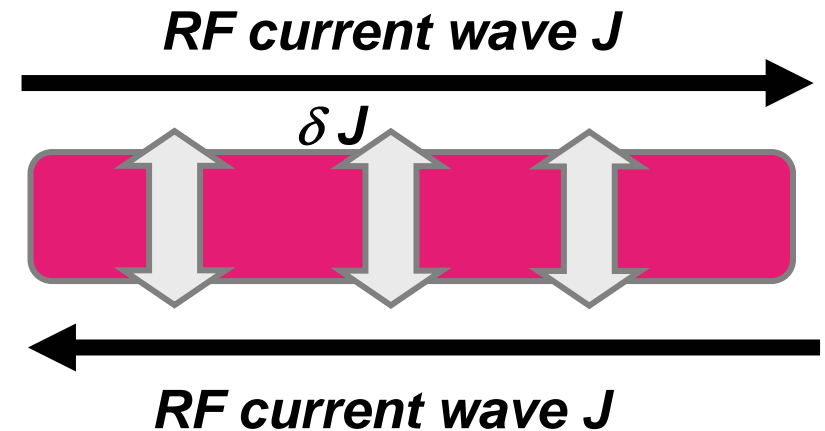


Physical origin: quasi-TEM **even** mode

the dispersion relation of the even mode reproduces the intuitive equivalent circuit of the standing wave effect:

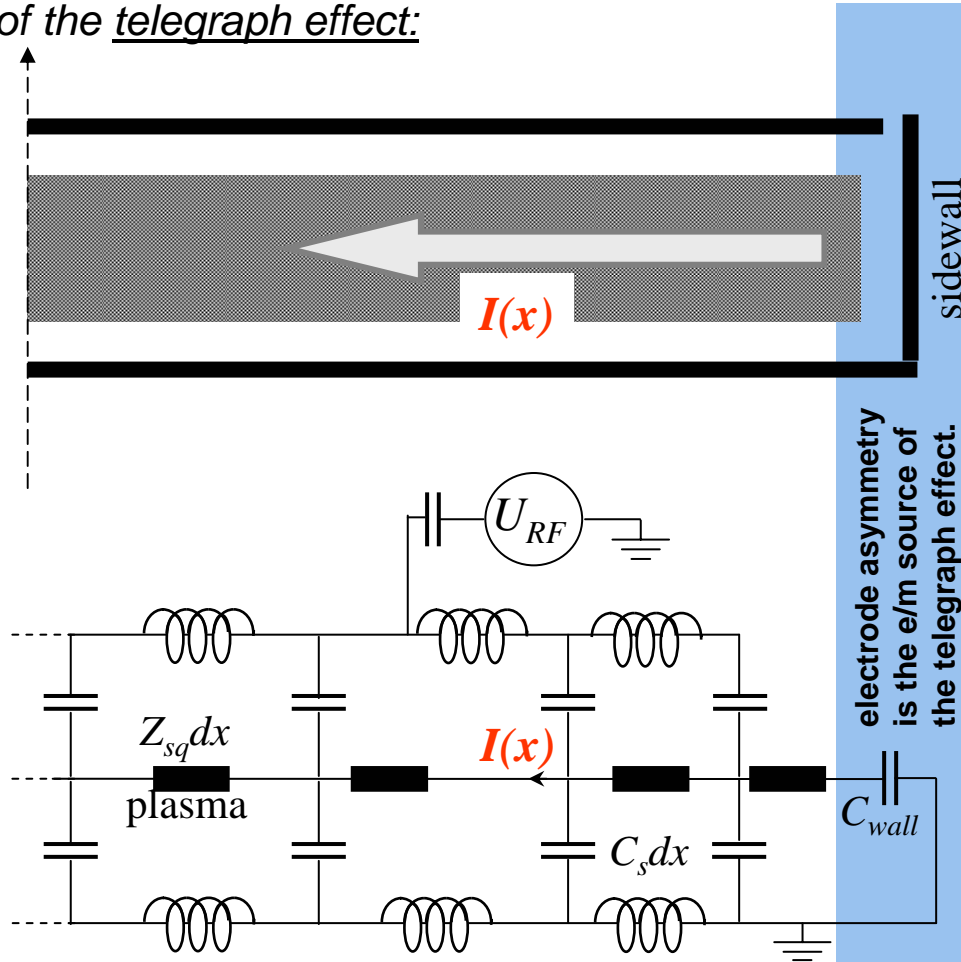


**plasma as
lossy dielectric
in a transmission line**

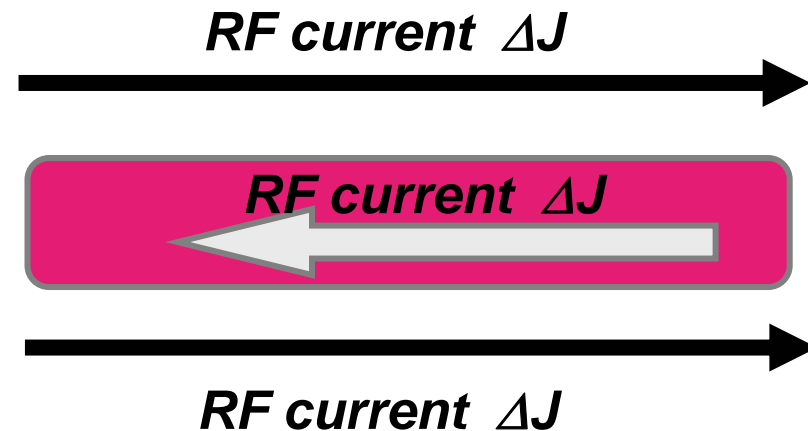


Physical origin: quasi-TEM **odd** mode

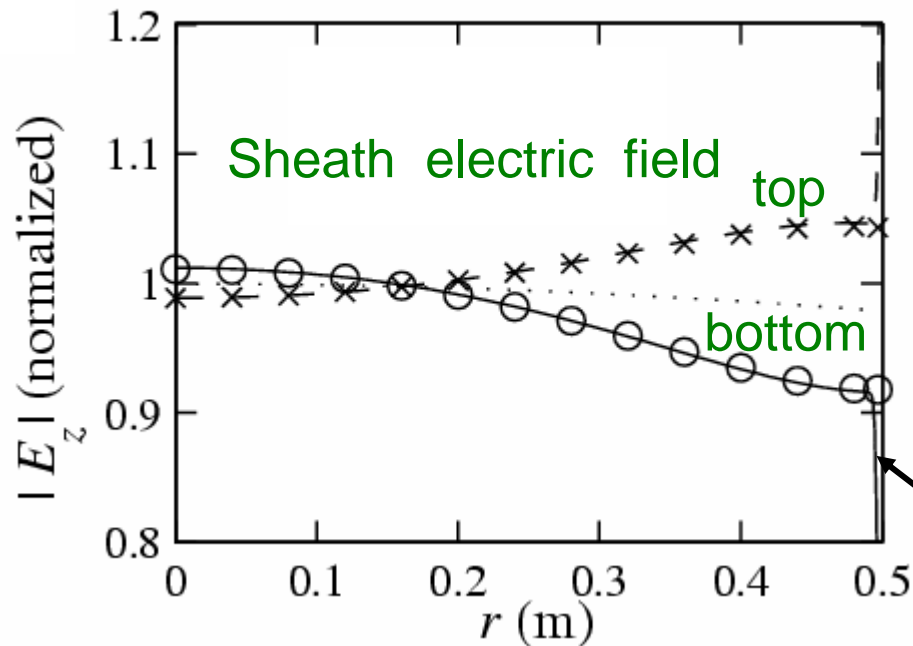
the dispersion relation of the odd mode reproduces the intuitive equivalent circuit of the telegraph effect:



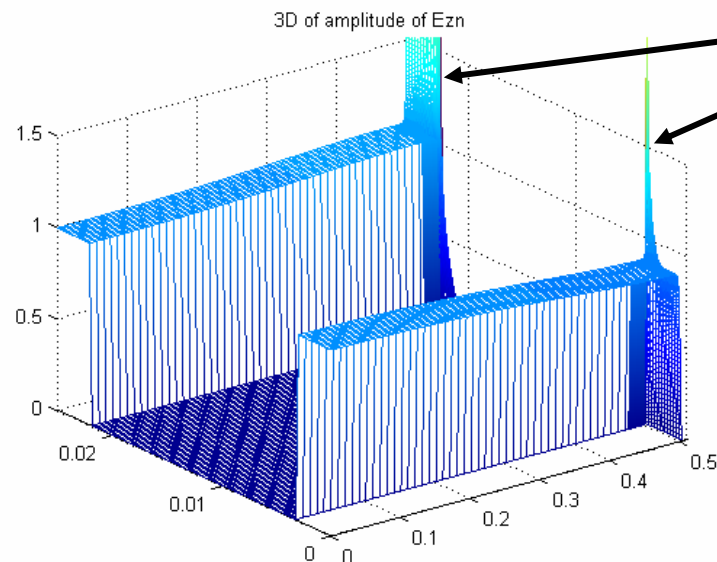
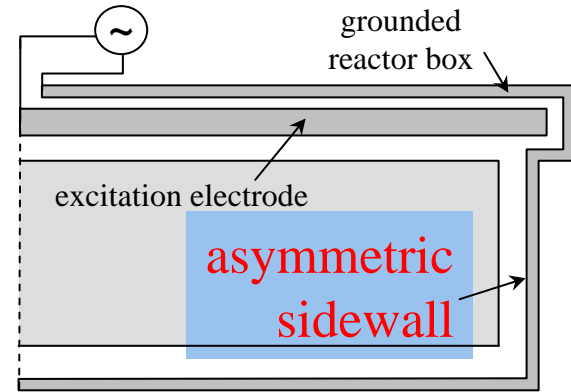
**plasma as
lossy conductor
in a transmission line**



Nonuniformity dominated by telegraph effect

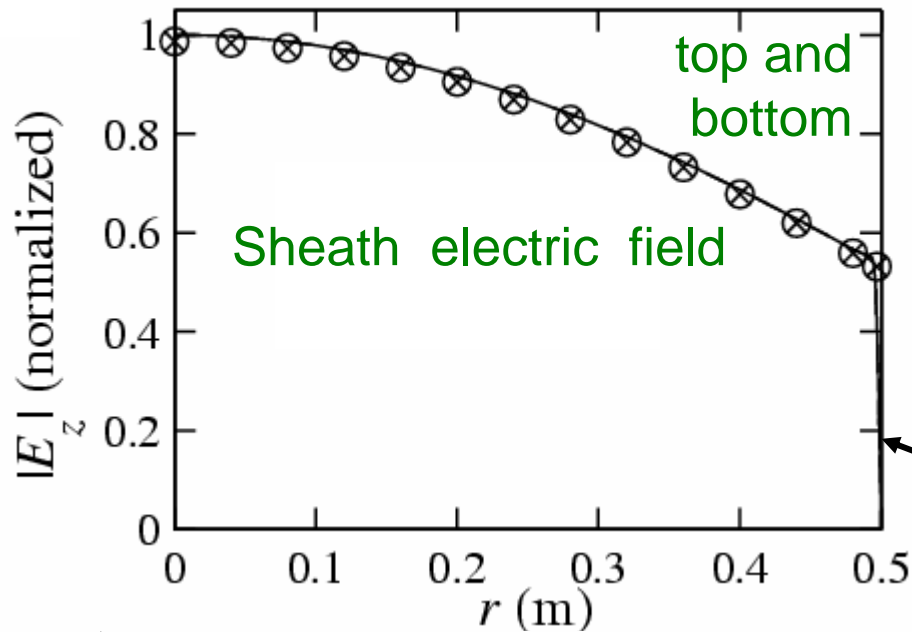


low frequency 13 MHz

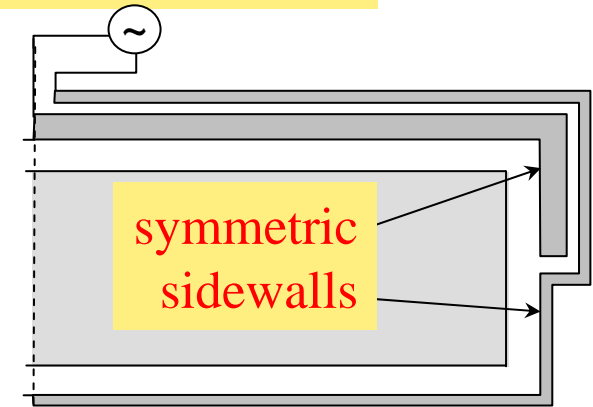


Edge Localized Modes
(not the same as in a tokamak!)
- fringing fields due to discontinuities
(in permittivity and in geometry)

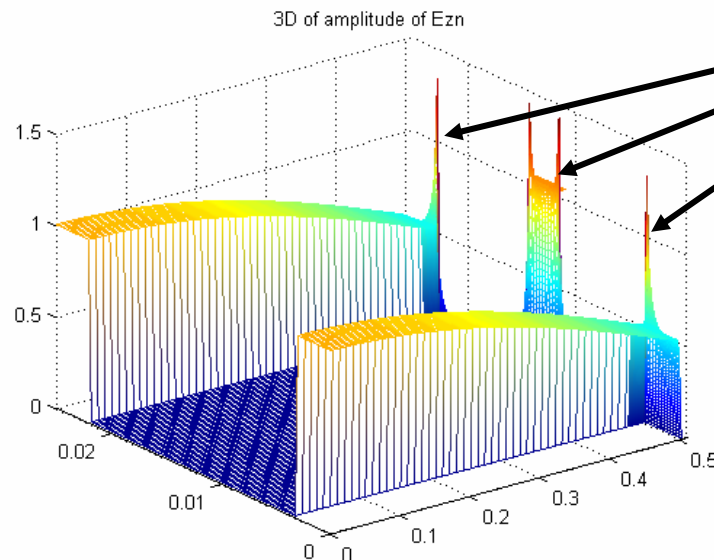
Nonuniformity of standing wave effect only



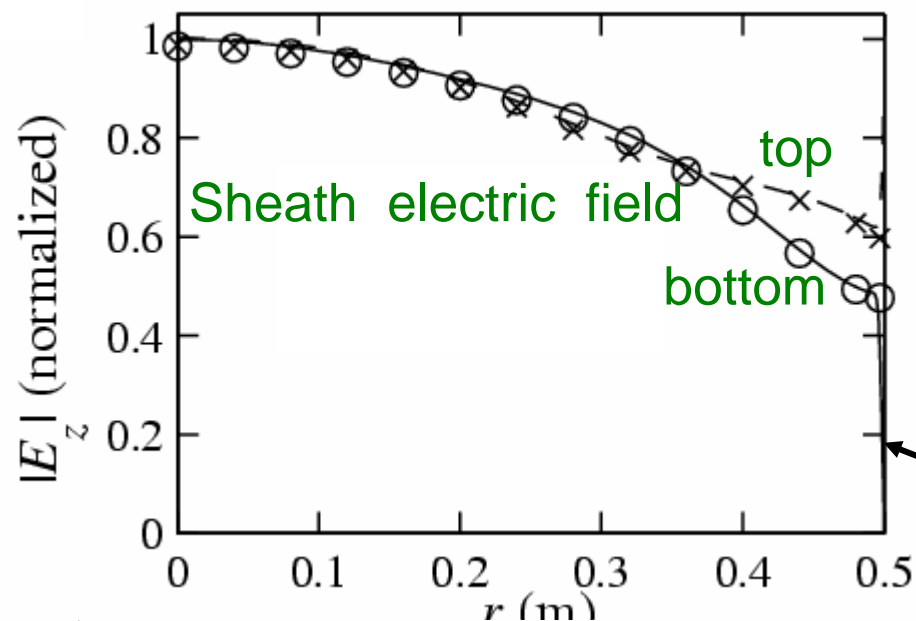
high frequency 67.8 MHz



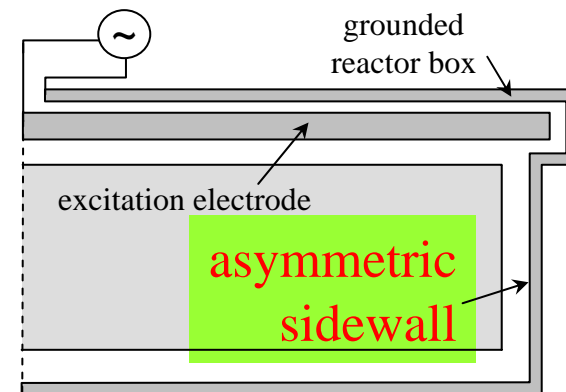
edge localized modes - fringing fields due to discontinuities



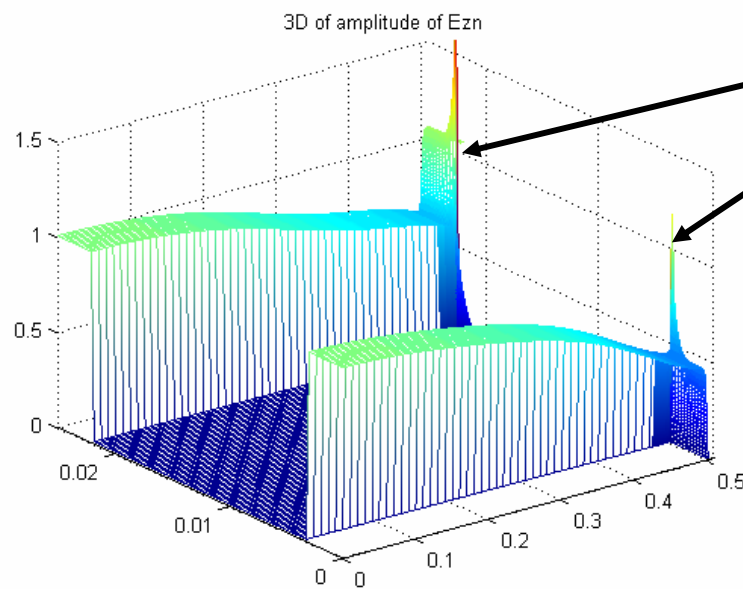
Standing wave & telegraph effect combined



high frequency 67.8 MHz

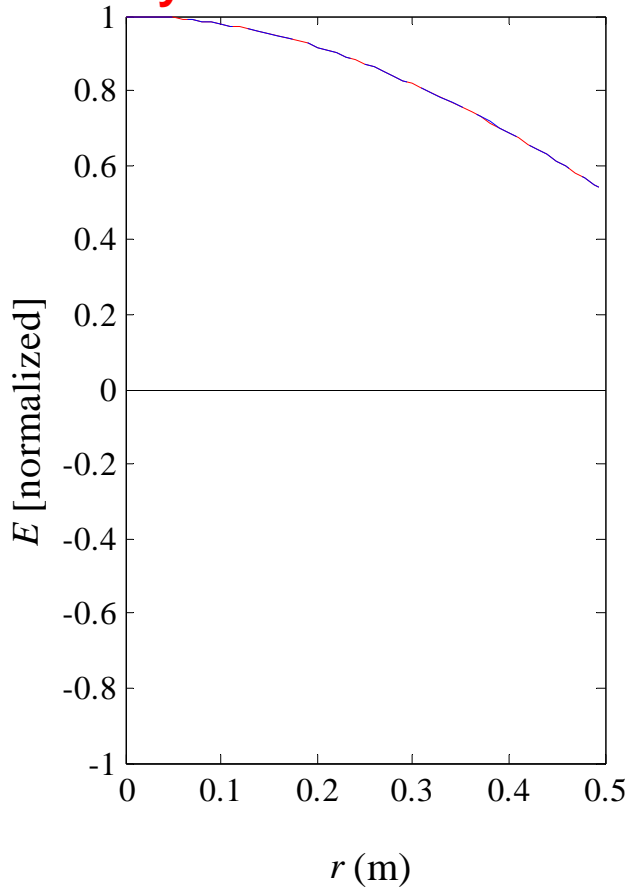


edge localized modes - fringing fields due to discontinuities

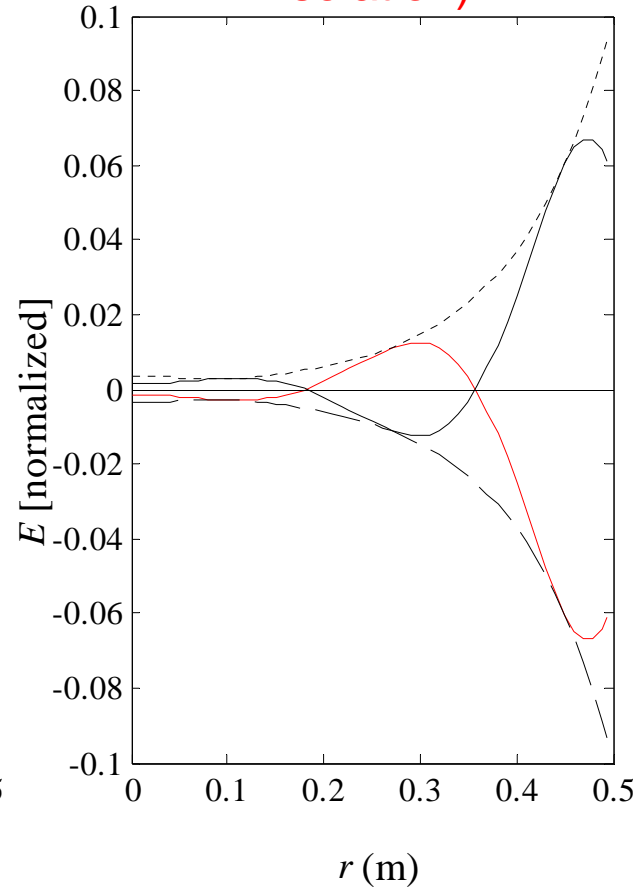


time series : $\omega t = 0$

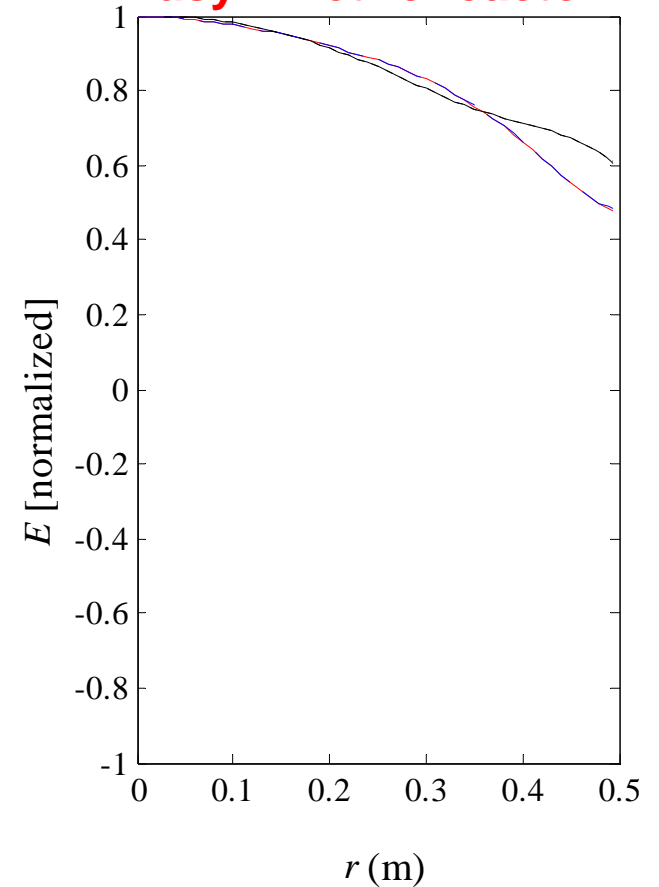
EVEN MODE
standing wave effect
**observed for
symmetric reactor**



ODD MODE
telegraph effect **x10**
(not observable
in isolation)

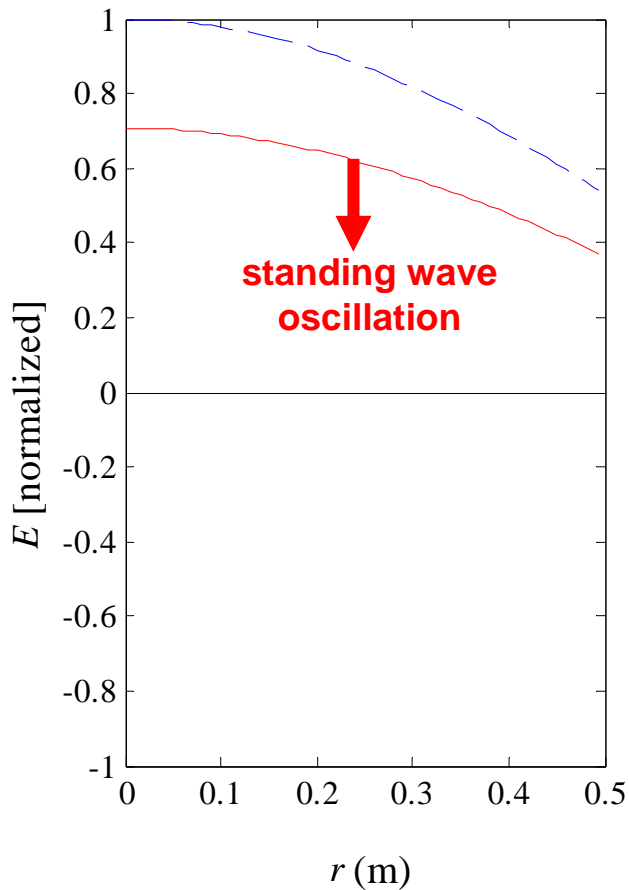


PLASMA RESPONSE
combined effect
**observed for
asymmetric reactor**

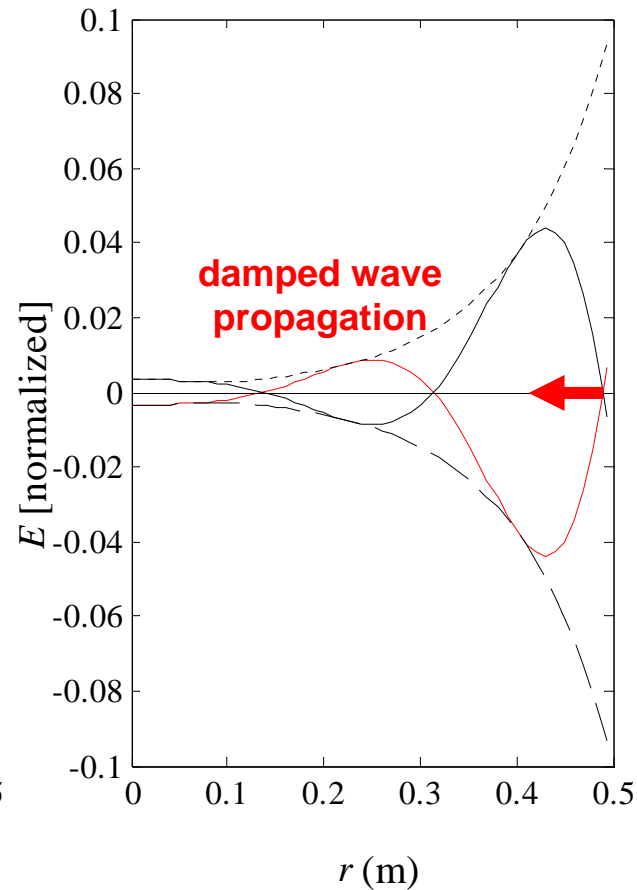


time series : $\omega t = 1\pi/4$

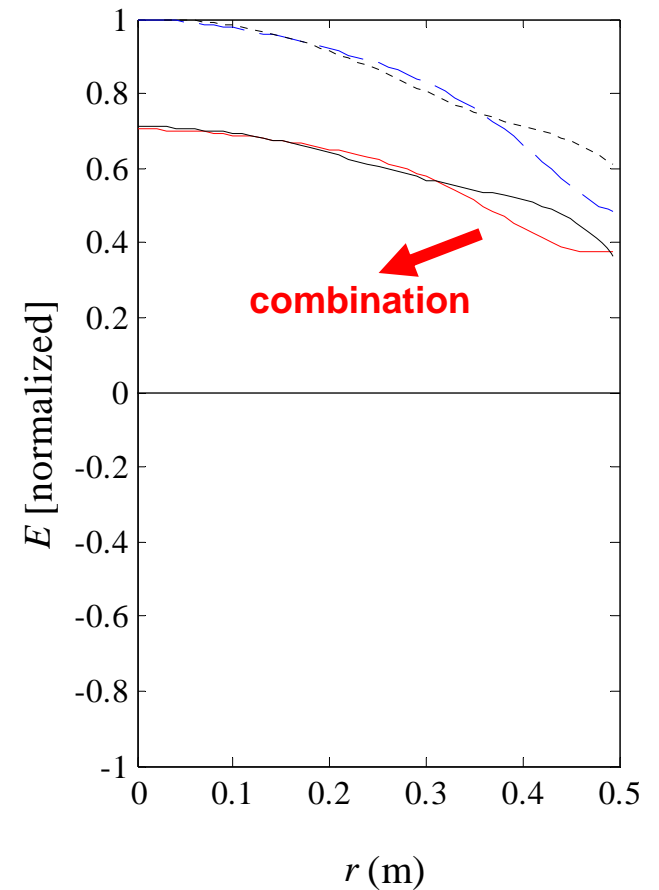
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

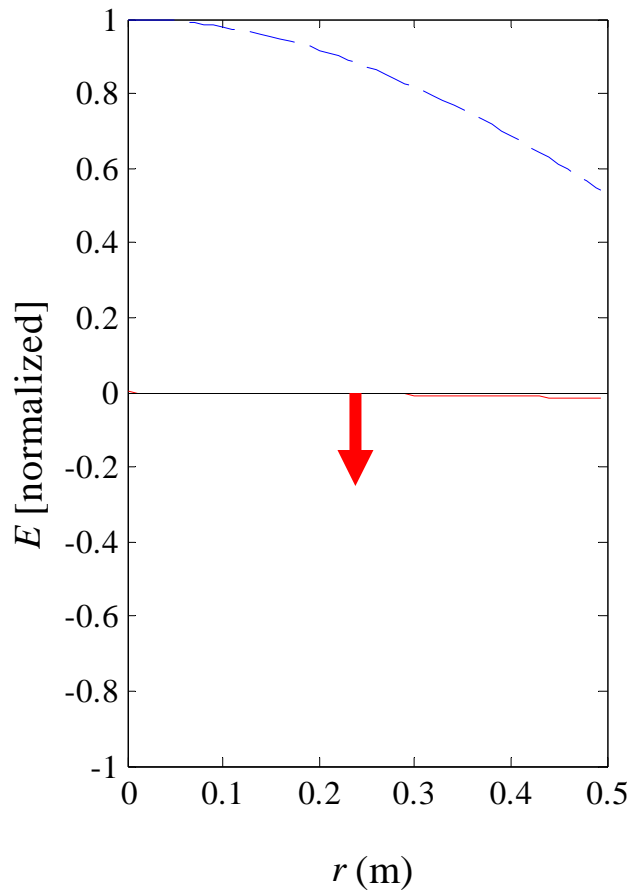


PLASMA RESPONSE
combined effect

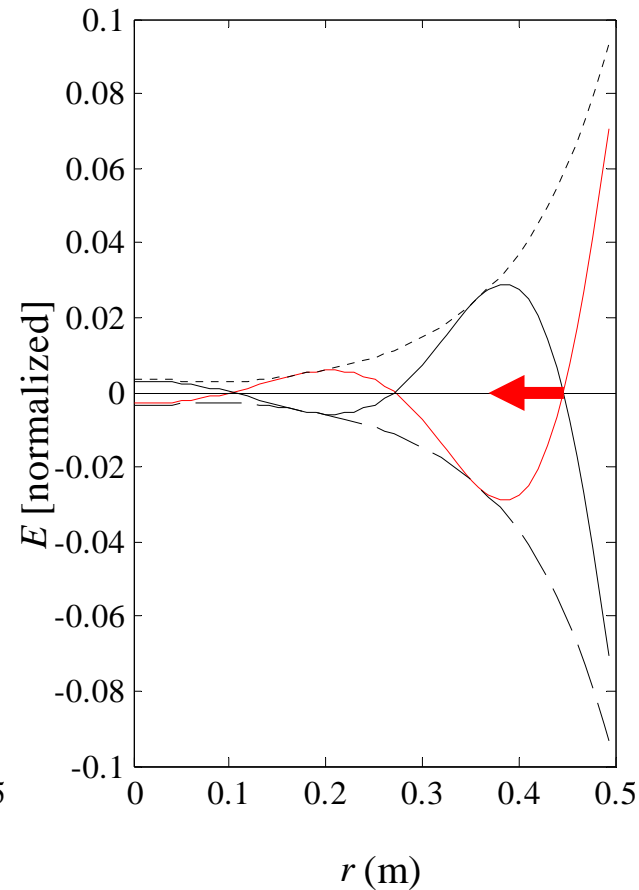


time series : $\omega t = 2\pi/4$

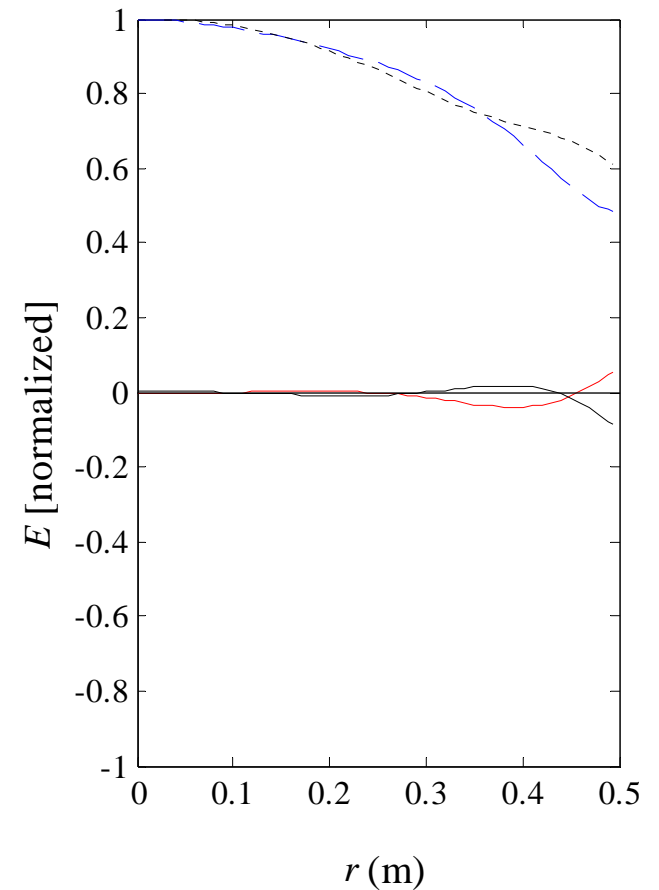
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

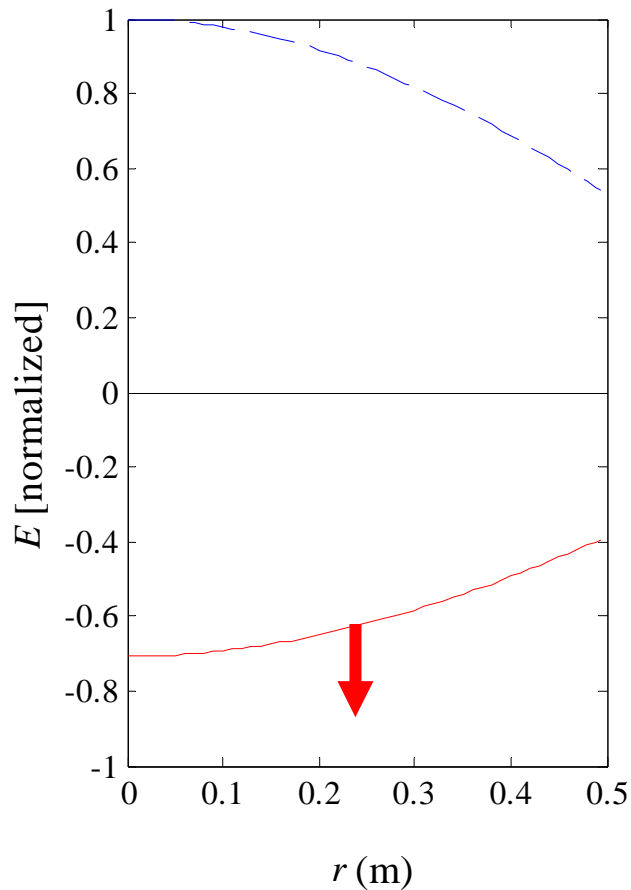


PLASMA RESPONSE
combined effect

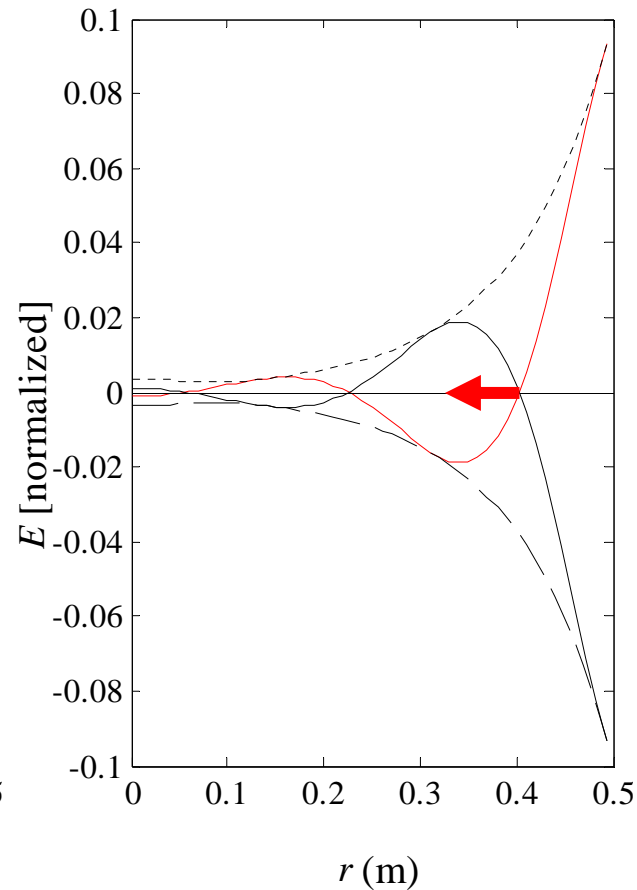


time series : $\omega t = 3\pi/4$

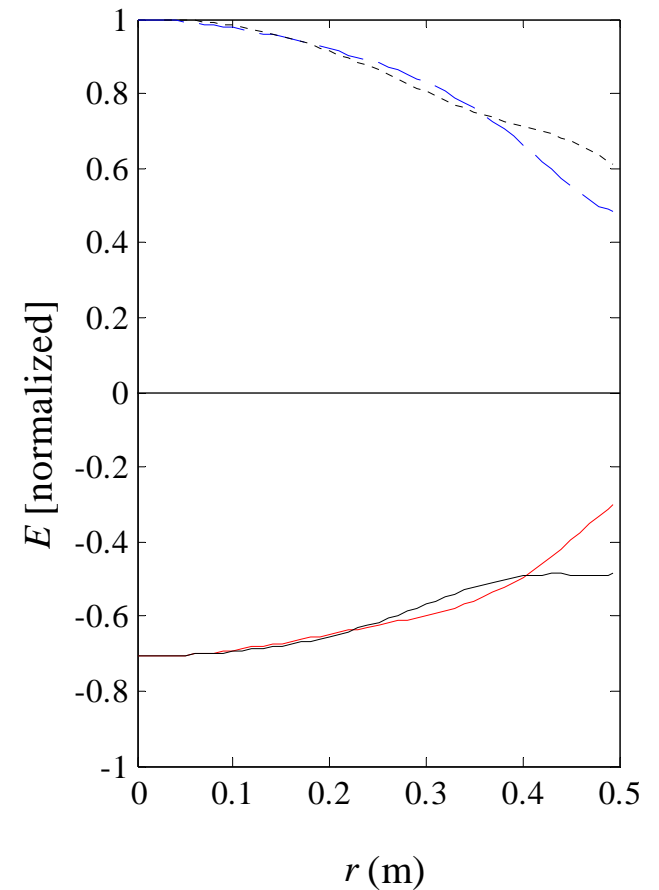
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

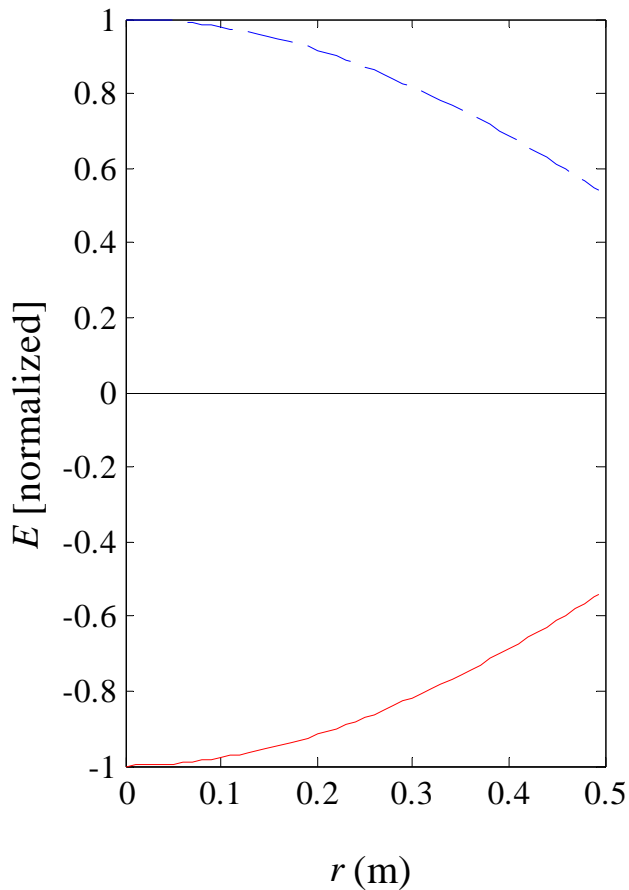


PLASMA RESPONSE
combined effect

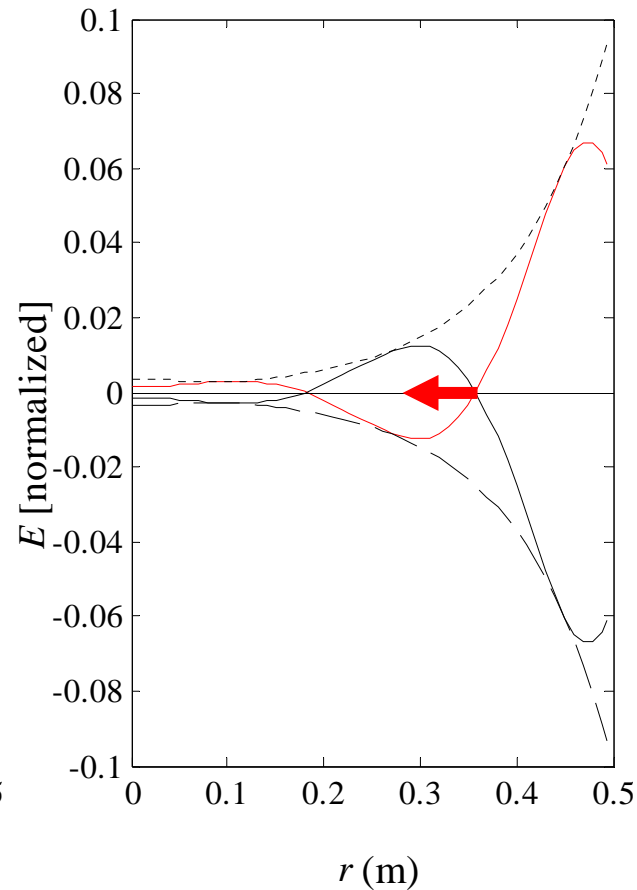


time series : $\omega t = 4\pi/4$

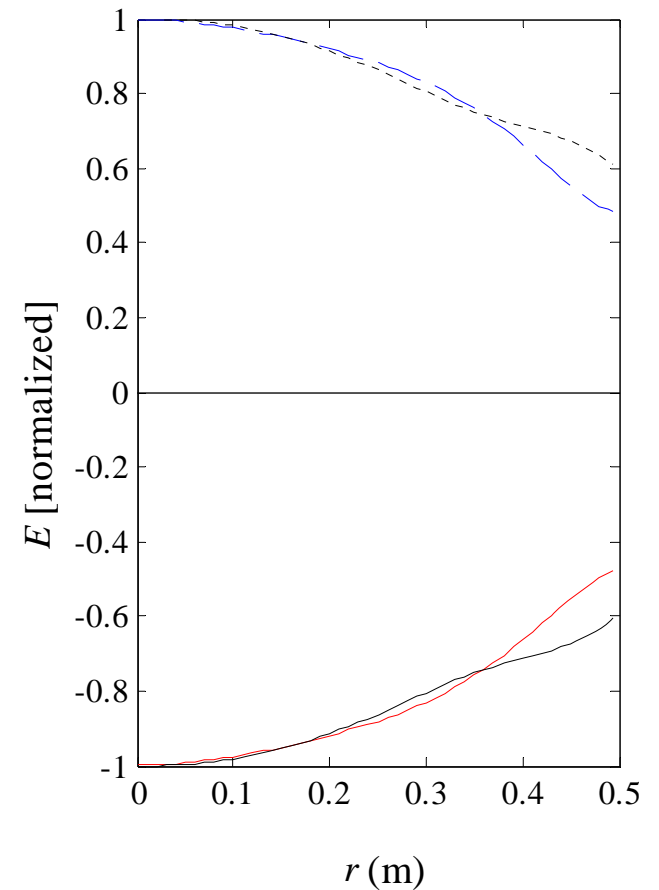
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

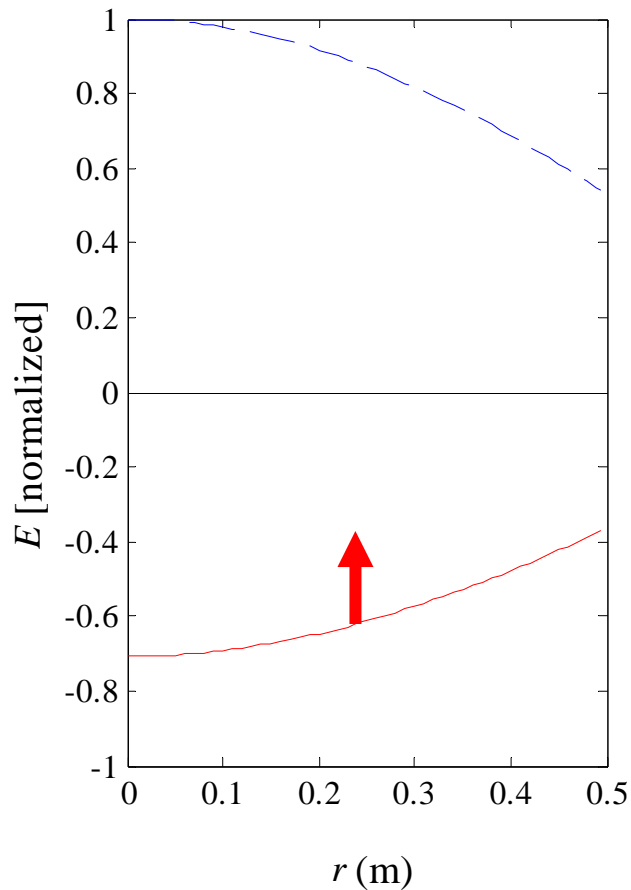


PLASMA RESPONSE
combined effect

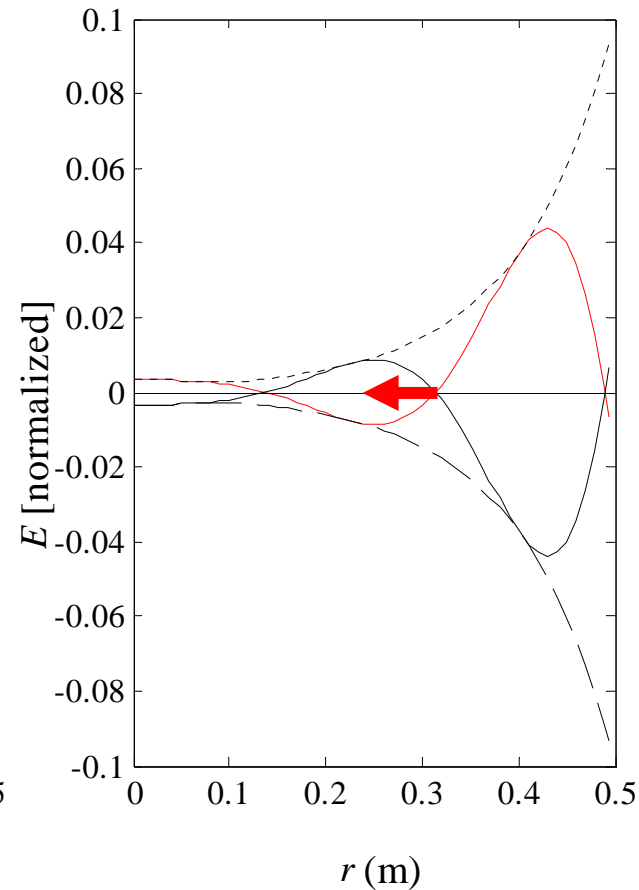


time series : $\omega t = 5\pi/4$

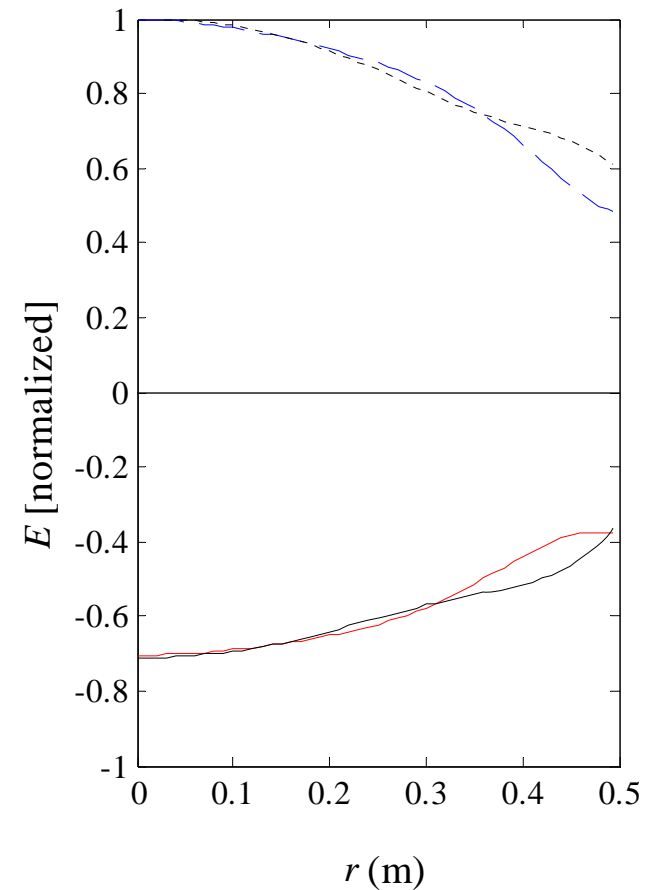
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

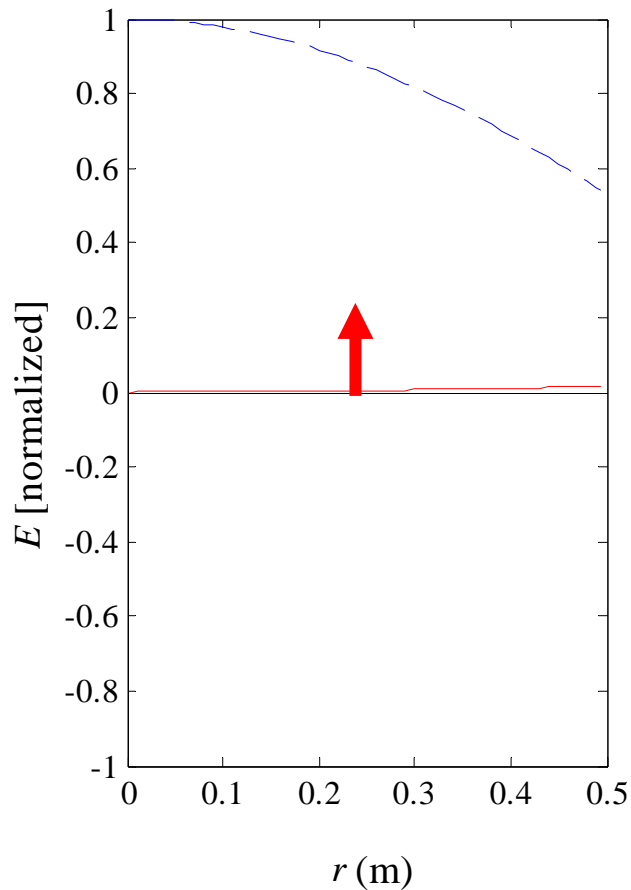


PLASMA RESPONSE
combined effect

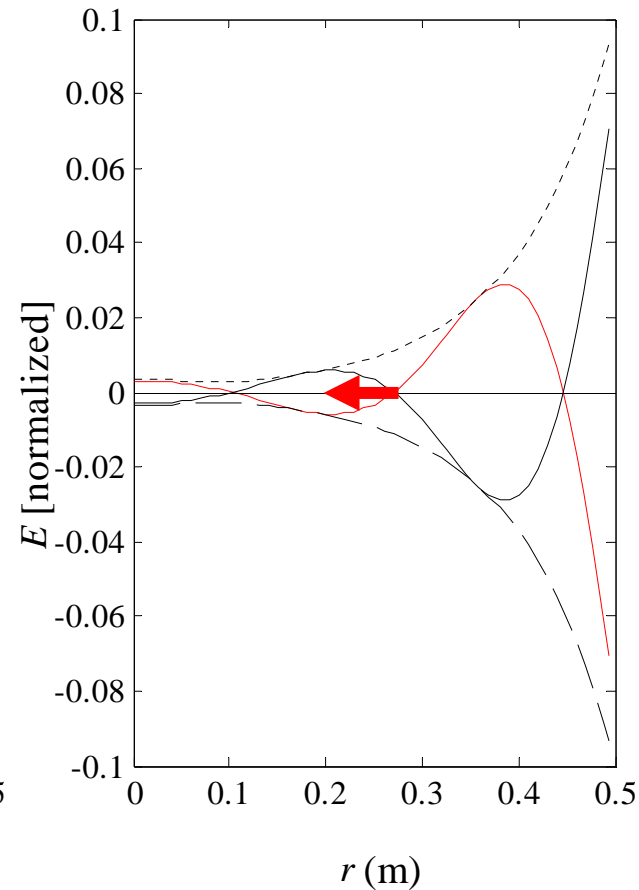


time series : $\omega t = 6\pi/4$

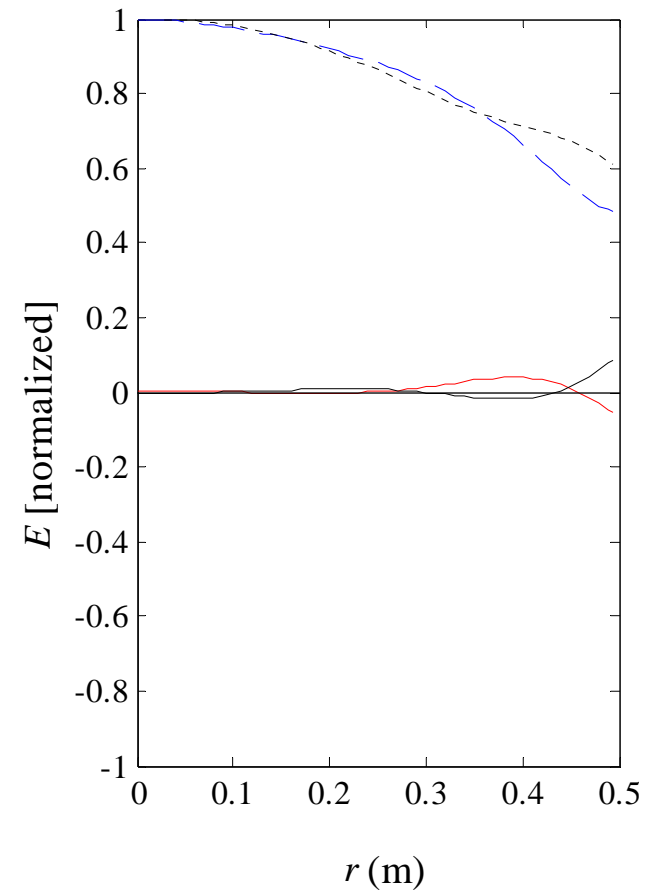
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

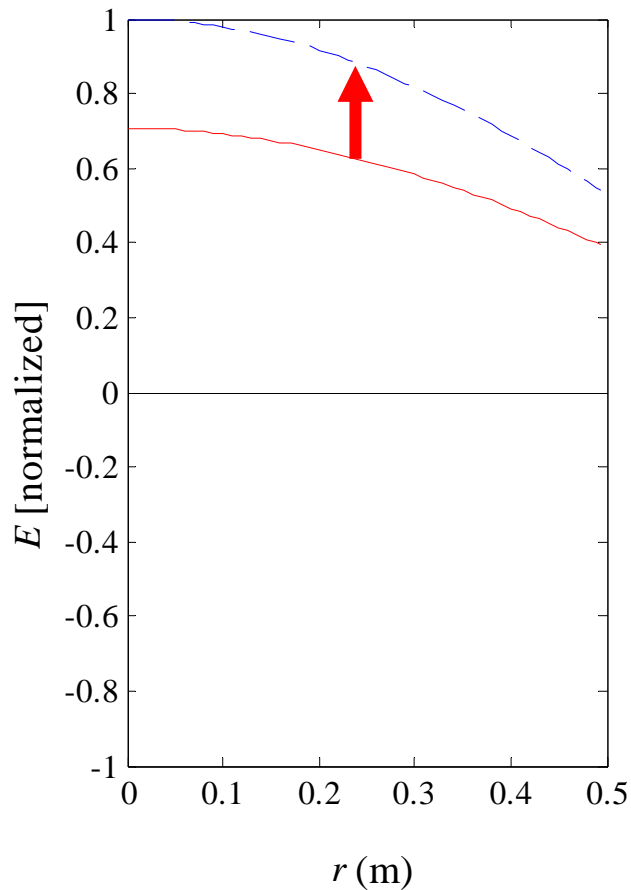


PLASMA RESPONSE
combined effect

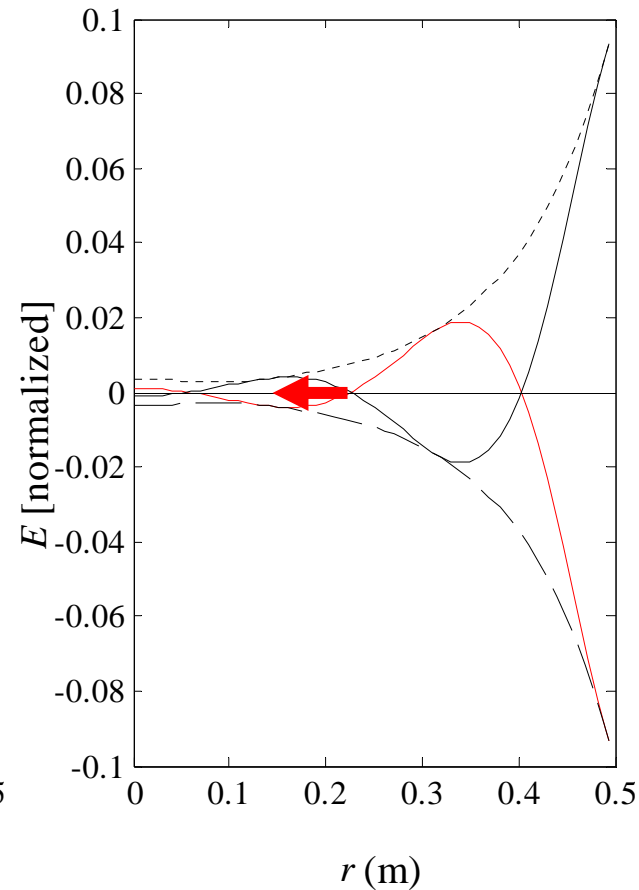


time series : $\omega t = 7\pi/4$

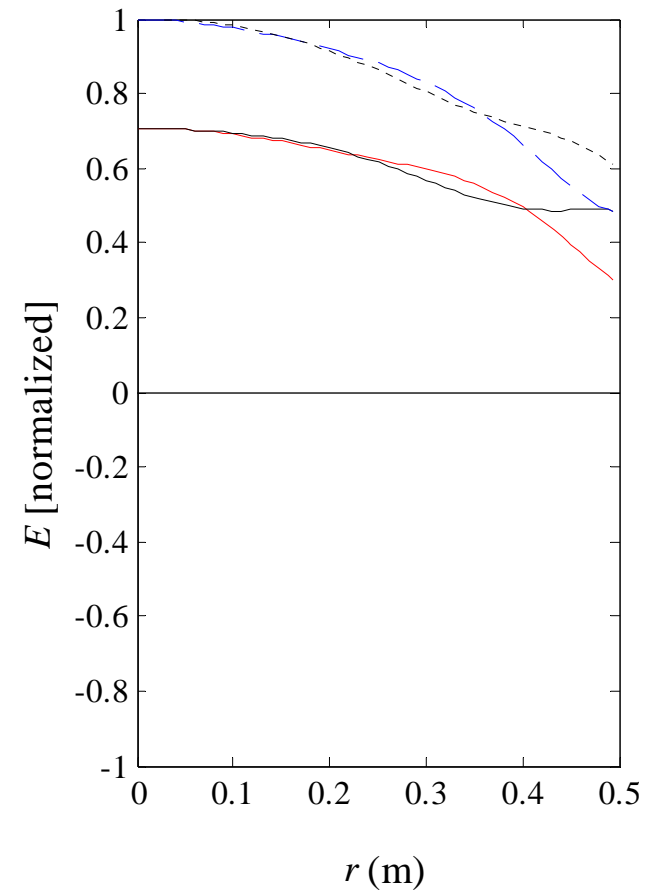
EVEN MODE
standing wave effect



ODD MODE
telegraph effect **x10**

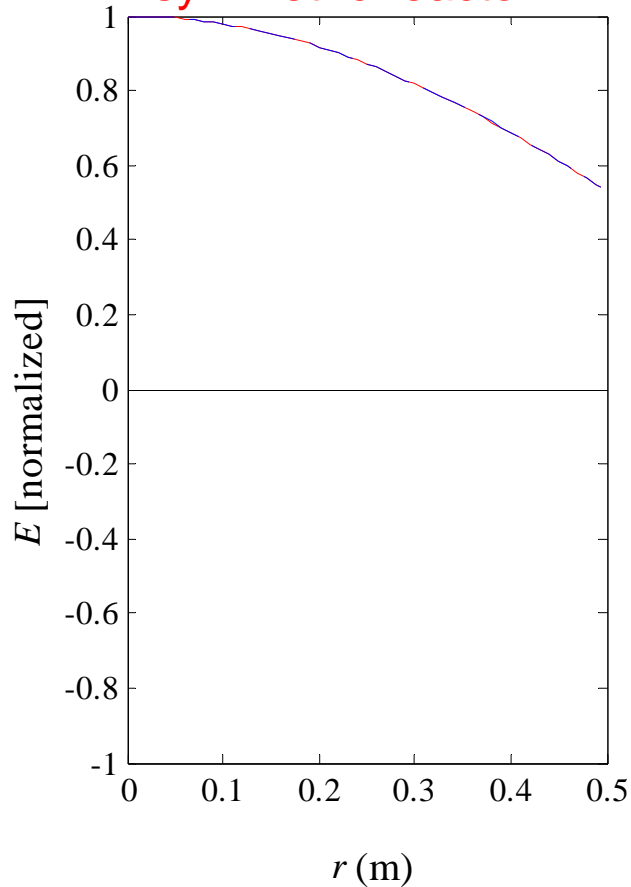


PLASMA RESPONSE
combined effect

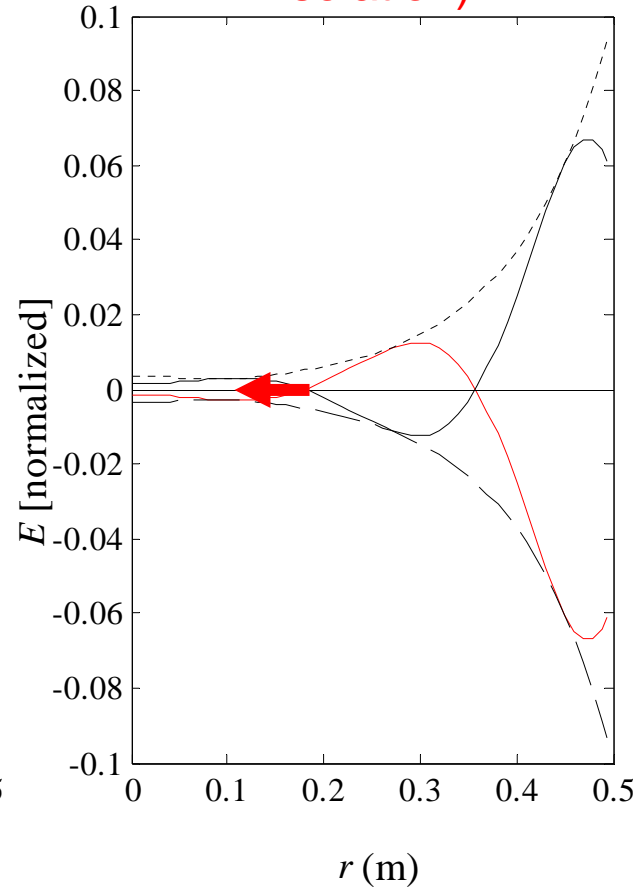


time series : $\omega t = 8\pi/4$

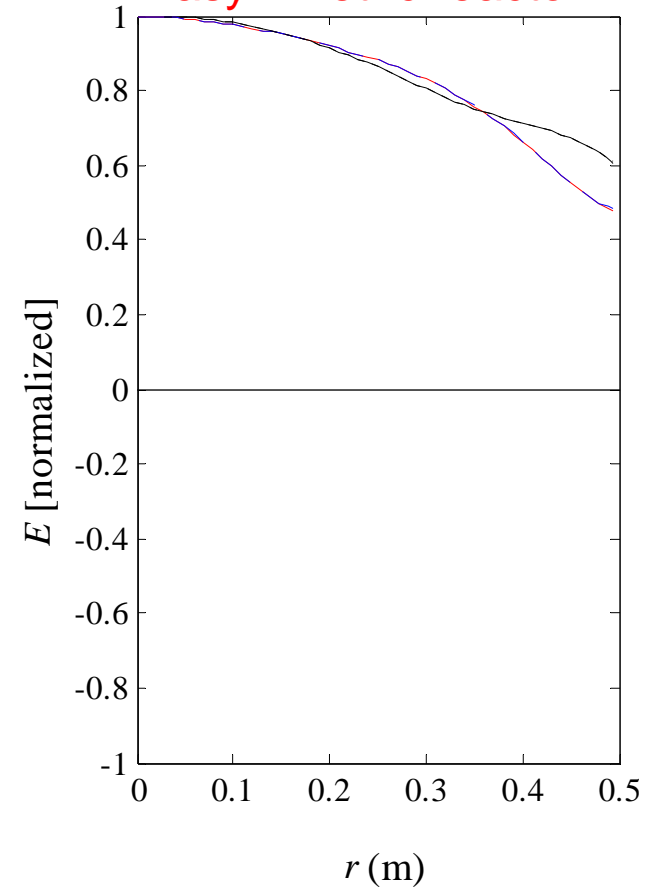
EVEN MODE
standing wave effect
observed for
symmetric reactor



ODD MODE
telegraph effect $\times 10$
(not observable
in isolation)

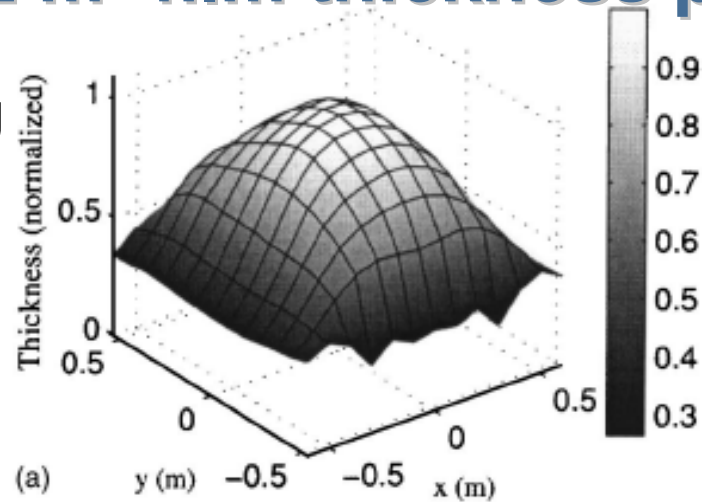


PLASMA RESPONSE
combined effect
observed for
asymmetric reactor



1.2 m² film thickness profiles - individual effects

standing
wave;
parallel
plates



standing
wave;
lens

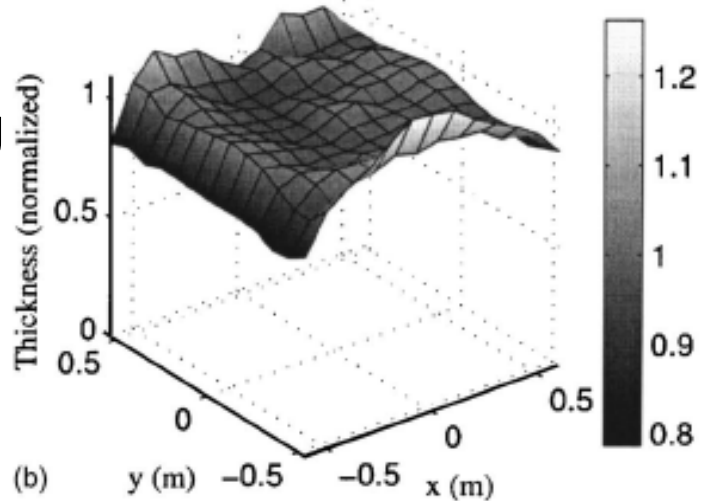
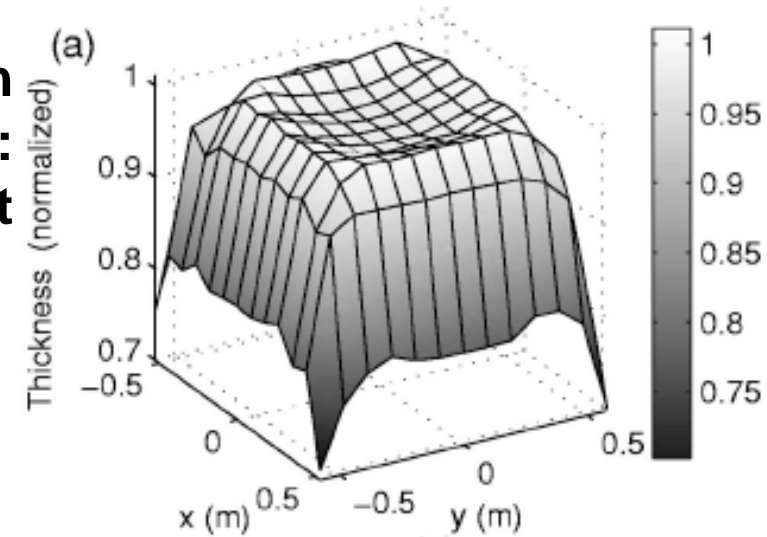


FIG. 5. Normalized α -Si:H film thickness uniformity deposited on a 1.1×1.2 m² substrate placed on the ground floor of a KAI-1200 asymmetric reactor at 40.7 MHz excitation frequency, 0.5 slm of silane and 0.5 slm of hydrogen at 0.5 mbar, and 400 W input power. (a) is for the parallel plate configuration and (b) for the shaped rf electrode configuration.

L. Sansonnens, H. Schmidt, A. A. Howling, Ch. Hollenstein, Ch. Ellert, A. Buechel, J. Vac. Sci. Technol. **A24**, 1425 (2006)

telegraph
effect:
experiment



telegraph
effect:
model

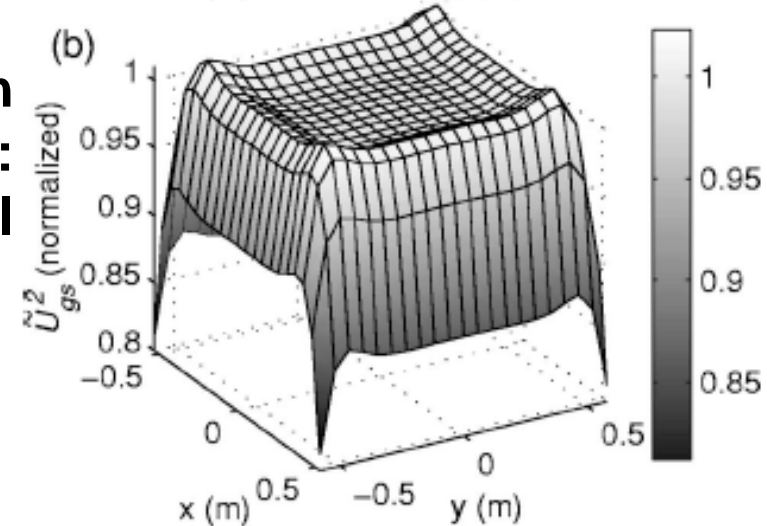


FIG. 4. (a) Normalized α -Si:H film thickness uniformity deposited on a 1.1 m by 1.2 m substrate placed on the ground floor of a KAI-1200 asymmetric reactor and (b) square of the ground sheath rf voltage distribution above the substrate area calculated with $\delta=7$ cm.

L. Sansonnens, B. Strahm, L. Derendinger, A. A. Howling, Ch. Hollenstein, Ch. Ellert, J.P. M. Schmittl, J. Vac. Sci. Technol. **A23**, 922 (2005)

Electromagnetic summary

Only even and odd quasi-TEM waves, which have no low-frequency cut-off, can propagate into a plasma reactor. They determine the electromagnetic fields within the reactor volume.

The rf excitation voltage of the even quasi-TEM wave propagates along the electrodes and gives rise to the standing wave effect. This nonuniformity can be corrected using a shaped electrode.

In asymmetric reactors, the rf plasma potential perturbation of the odd quasi-TEM wave propagates along the plasma. This is the telegraph effect; it is absent in reactors with symmetric electrodes.

If these two sources of electromagnetic nonuniformity are corrected, only edge-localized evanescent modes remain.

L. Sansonnens, A. A. Howling and Ch. Hollenstein, *Plasma Sources Sci. Technol.* **15** 302 (2006)
A. A. Howling, L. Sansonnens and Ch. Hollenstein, *Thin Solid Films* **515** 5059 (2007)

Intermediate Conclusions

- Require uniform RF voltage. If an electrode dimension is $> (\text{RF vacuum wavelength}/10)$, then special precautions are necessary to avoid the standing wave effect. This is therefore more likely to be a problem at Very High Frequency.
- Use symmetric electrodes to avoid telegraph effect (RF current injection from asymmetric sidewalls).
- Avoid edge fringing fields due to discontinuities in permittivity and geometry.

Refs. L. Sansonnens, A. A. Howling and Ch. Hollenstein, *Plasma Sources Sci. Technol.* **15** 302 (2006)
A. A. Howling, L. Sansonnens and Ch. Hollenstein, *Thin Solid Films* **515** 5059 (2007)